Keck Adaptive Optics Note 716

Next Generation Adaptive Optics Preliminary Design Wavefront Error Budgets

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Abstract

The purpose of this note is to summarize the wavefront error and encircled energy budgets for the Next-Generation Adaptive Optics (NGAO) system at the time of the NGAO Preliminary Design Review.

These budgets are based upon a set of architecture design choices and functional requirements flowdowns consistent with the NGAO System Requirements, which are maintained in an online Requirements Management database product, Contour, developed by JAMA Software, Inc. and commercially licensed by W.M. Keck Observatory.

Revision Sheet

Release No.	Date	Revision Description
Rev 1.0	5/12/10	Initial release

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1 Introduction

1.1 Acronyms and Definitions

DAVINCI	A new science instrument under development as part of NGAO
DD	Detailed Design
EncE	Encircled Energy
EnsqE	Ensquared Energy
FoV	Field of View (the field observed by a single detector array)
FoR	Field of Regard (the technical or patrol range of a sensor)
FWHM	Full-Width at Half-Maximum = 2.355 σ, for a Gaussian distribution
HO WFS	High-order wavefront sensor
IFU or IFS	Integral Field (Unit) Spectrograph
LGS	Laser Guide Star
LO WFS	Low-Order Wavefront Sensor
mas	Milliarcseconds
NGAO	Next-Generation Adaptive Optics
NGS	Natural Guide Star
NGWFC	Next-Generation Wavefront Controller
PD	Preliminary Design
PSF	Point Spread Function
RMS	Root Mean-Squared
SD	System Design
TT	Tip-tilt
TWFS	Truth Wavefront Sensor
WFE	Wavefront Error
”	arcseconds
’	arcminutes

1.2 Purpose

The purpose of this document is to describe the expected wavefront error performance of NGAO, the methodology for constructing and maintaining NGAO error budgets, and to investigate the robustness of NGAO performance to various changes in input assumptions.

1.3 Scope

This document includes all defined NGAO science case error budgets, sample TT sharpening budgets, and numerous trade studies performed to capture NGAO performance sensitivities to environmental, observational, and technical assumptions. We include a summary of the assumptions, architecture choices, performance flowdown requirements, validation results, external comparisons, and other supporting materials for our performance estimates.

1.4 Related Documents

1.4.1 Configuration-Controlled Documents

- KAON 550, NGAO System Configurations
- KAON 636, Observing Operations Concept Document
- KAON 642, Design Changes in Support of Build-to-Cost
- KAON 721, Wavefront Error Budget Tool
- KAON 722, NGAO High-Contrast Error Budget Tool
- KAON 723, Performance Flowdown Budgets

1.4.2 Previous NGAO Performance Documents

- KAON 452, MOAO versus MCAO Trade Study Report
- KAON 465, NGAO LGS Wavefront Sensor: Type and Number of Subapertures Trade Study
- KAON 470, NGAO Sky Coverage Modeling
- KAON 471, NGAO Wavefront Error and Ensquared Energy Budgets (for System Design Phase)
- KAON 475, Tomography Codes Comparison and Validation for NGAO
- KAON 480, Astrometry for NGAO
- KAON 492, NGAO Null-Mode and Quadratic Mode Tomography Error
- KAON 497, NGAO High-Contrast and Companion Sensitivity Performance Budget
- KAON 503, Mauna Kea Ridge Turbulence Models
- KAON 504, NGAO Performance vs. Technical Field of View for LOWFS Guide Stars
- KAON 594, Plan to Address Phased Implementation and Descope Options
- KAON 601, NGAO Point and Shoot (SPIE 2008)
- KAON 621, Noise Propagator for Laser Tomography AO
- KAON 629, Error Budget Comparison with NFIRAOS
- KAON 635, Point & Shoot Study
- KAON 644, Build-to-Cost Architecture Performance Analysis
- KAON 686, Laser Launch Facility System Performance
- KAON 710, Latency, Bandwidth, and Control Loop Residual Relationships

1.4.3 Keck AO Performance Analyses

- KAON 461, Wavefront Error Budget Predictions & Measured Performance for Current & Upgraded Keck AO
- KAON 462, NGAO Trade Study: Keck AO Upgrade
- KAON 469, Effect of Keck Segment Figure Errors on Keck AO Performance
- KAON 482, Keck Telescope Wavefront Error Trade Study
- KAON 500, Keck AO Upgrade Feasibility

1.4.4 References

- “The W. M. Keck Observatory Scientific Strategic Plan 2009”, W. M. Keck Observatory.
- CIN 626, PALM-3000 Error Budget Summary
- J. W. Hardy, *Adaptive Optics for Astronomical Telescopes* (Oxford U. Press, 1998).
- KAON 416, Atmospheric Sodium Density form Keck LGS Photometry
- KAON 427, Variable versus Fixed LGS Asterism
- KAON 465, NGAO LGS Wavefront Sensor: Type and number of Subapertures Trade Study
- KAON 477, Modeling Low Order Aberrations in Laser Guide Star AO Systems (OE 2007)

- KAON 478, Modeling Laser Guide Star Aberrations (OSA 2007)
- KAON 662, Beam Transport Optics
- KAON 685, Opto-mechanical Design
- KAON 692, LGS Wavefront Sensor Preliminary Design
- KAON 695, Beam Generation System
- KAON 704, Opto-mechanical Registration Tolerances for “go-to” Adaptive Optics
- KAON 708, Limit to AO Observations from Altitude-Azimuth Telescope Mounts.
- KAON 718, NGAO LGS and NGS Wavefront Sensor Cameras
- KAON 729, Natural Guide Star Wavefront Sensor

2 Background

2.1 High-angular Resolution Science Priority

W. M. Keck Observatory, through a series of science strategic planning exercises beginning at least as early as 2003, and again revised in November 2005, Fall 2008, and Spring 2009, has steadfastly maintained “High Angular Resolution Astrophysics” as one of four top priorities that define the Keck Strategic Mission. As the top-ranked initiative in the scope of project over $20M, the 2009 Plan specifically note the scientific premium upon NGAO

“obtaining the highest spatial resolution possible and also visible band capability” (pg. 5)

The Plan further identifies the following key new capabilities for NGAO:

“Near diffraction-limited observations in the near-IR (K-Strehl ~80%); AO correction at red wavelengths (0.65-1.0mm); Increased sky coverage; Improved angular resolution, sensitivity, and contrast; Improved photometric and astrometric accuracy, Imaging and integral field spectroscopy.” (pg. 22)

Within this context, the NGAO project has undertaken a series of performance budget developments in the system design (SD) and preliminary design (PD) phases that are intended to:

1. Facilitate the capture of high-level system requirements
2. Support the flow-down of system requirements to functional requirements imposed upon individual NGAO subsystems
3. Assess technical and cost tradeoffs across the project
4. Identify and support management of project technical risk areas
5. Support science team development of predictive NGAO science models and observing scenarios.

3 Performance Requirements Development and Flow-down

3.1 Build-to-Cost Architecture Changes and Performance Revisions

Subsequent to the System Design Review (SDR), revisions to the system architecture were necessitated by new sponsor guidance of a cost-capped funding envelope for NGAO, known as Build-to-Cost (B2C). This necessitated cost-saving architectural changes, which were documented in KAON 642, Design

Changes in Support of Build-to-Cost. A “delta-assessment” of the B2C changes on system wavefront error performance was performed in KAON 644, Build-to-Cost Architecture Performance Analysis, which provided sufficient confidence on the ultimate ability of NGAO to deliver its primary science objectives. An external review panel agreed with this assessment, as described in KAON 650, Build-to-Cost Reviewer Report, allowing us to proceed with the remainder of the PD phase. For the systems engineering group, this included capture of key performance flowdown requirements, improved analysis of key error budget terms, and refinement of science cases.

3.2 Requirements Capture Process

Early in the SD phase, the NGAO project developed a strategy for the interpretation of science-based requirements, as captured in KAON 455, “Science Case Requirements Document”, into NGAO performance requirements. This process is described in Figure 1. It is based upon the development of a number of distinct NGAO science cases, the identification of key science drivers (i.e. the science requirements that force the architecture and performance of the system), the evaluation of these drivers against evolving performance models (engineering models and/or wave optics simulations), and the iterative adoption of a self-consistent set of science-driven performance requirements and system architecture choices.

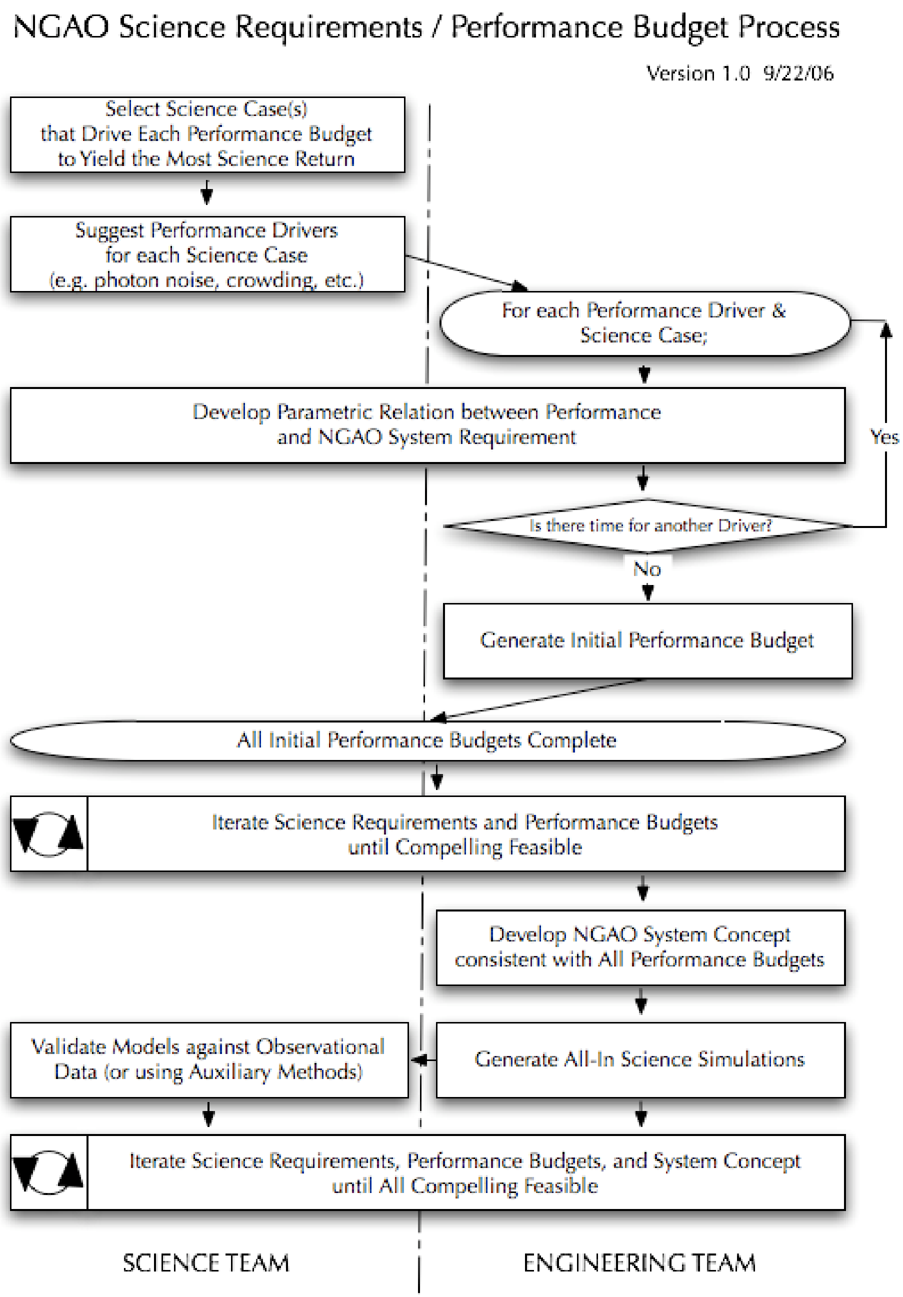

Figure 1. Performance requirements development process

For our System Design Review (SDR), this process had supported both the NGAO architecture downselect process (KAON 499, "NGAO System Architecture Definition"), and generated the following performance budgets:

- Wavefront Error and Ensquared Energy
- Photometric Precision
- Astrometric Accuracy
- High-Contrast

- Transmission and Background
- Polarimetric Precision
- Observing Efficiency
- System Uptime

The SD phase development of these budgets is documented in KAON 491, "NGAO system performance summary".

After our SDR was held in April 2008, new sponsor guidance to proceed with a cost-capped re-scoping of the project (aka "Build-to-Cost") required reiteration of the process in Figure 1. Upon the establishment of the cost-saving changes described in KAON 642, "Design Changes in Support of Build-to-Cost", the performance budgets were partially reevaluated in KAON 644, "Build-to-Cost Architecture Performance Analysis". Based on KAON 644, additional feedback from the science team was received.

As a result of the initial SD phase reports from individual working groups addressing each performance budget, combined with the compressed budget and schedule induced by the Built-to-Cost project re-scope, NGAO senior management curtailed further development of performance budgets for both Photometric Precision (KAON 474, "AO Photometry for NGAO") and Polarimetric Precision, although polarization issues have been considered for Keck Interferometer support (KAON 428, "Implications and Requirements for Interferometry with NGAO"; KAON 748, "NGAO & the Keck Interferometer".)

For reference the historical transition of the performance requirements, including current Keck AO Performance as documented in KAON 461, is shown in

Table 1. In general, the imposed cost cap has resulted in the performance degradation of some science cases, but the close iterations between technical and science teams on science priorities has allowed performance improvement for certain key science cases.

NGAO Key Science Case	2006 Keck 2 AO Performance in 75th Percentile Best Seeing (approx.)	Expected Keck 1 AO Performance in Median Seeing (approx.)	NGAO Requirements in Median Seeing			
			Proposal[1,2]	SDR	B2C	PDR
Galaxy Assembly	557[3]	529[4]	197[5]	257	204	185
Nearby AGN's	557[3]	529[4]	197[5]	N/A	182	181[6]
Galactic Center	401[7] in median seeing	387[8]	182	184	189	193
Exoplanets	378[9]	311[10]	N/A	155[10]	171	174
Minor Planets	557[3]	529[4]	131	175	177	181[11]
Io	258[12]	210[13]	125	148[13]	N/A	117

Table 1. Progression of Wavefront Error Performance Requirements to Date (Proposal = Project Initiation (June 2006); SDR = System Design Review (April 2008); B2C = Built-to-Cost (Aug 2008), PDR = Preliminary Design Review (June 2010), N/A = Not available).

During the NGAO preliminary design (PD) phase, as the initial high-level performance requirements were flowed down to subsystems and design decisions and constraints informed the maturity of the design, there has been additional iterations between the technical and science teams. In parallel, based on additional thinking of the observing scenarios and science objectives, revisions to the Key Science Cases have been provided (Max and McGrath, *KAON in preparation)*.

One outcome of the PD phase flowdown and pushback process was the tightening of the residual non-common-path and telescope jitter tip-tilt error requirements. At the same time, higher galactic latitude

[1] Slight revisions to the Key Science Cases have been made during PD phase. See McGrath and Max, "Science Case Parameters for Performance Budgets" for more details.
[2] June 20, 2006 NGAO Design and Development Proposal, Table 13.
[3] KAON 461, Table 1 for LGS mode with 18th magnitude TT star.
[4] KAON 461, Appendix 3 for LGS mode with 18th magnitude TT star.
[5] June 20, 2006 NGAO Design and Development Proposal, Figure 49, for 30% sky coverage, z = 30 deg, having 173 nm HO error and
[6] Performance increase driven by reduced FoR for this science case brought on by Build-to-Cost decision to eliminate a d-IFU instrument from the NGAO program.
[7] Jessica Lu, private communication, who reports NGWFC *median* performance of 401 nm RMS, or a K-Strehl of ~27% (75th percentile performance not available). This is broadly consistent with the report K-Strehl of 30% in Ghez, et al., *Astrophys. J.,* 635:1087-1094, 1995.
[8] Here, we assume Keck 1 LGS will provide the same high-order wavefront error improvement at GC as shown in KAON 461, Table 2, LGS case, namely the subtraction of 105 nm in quadrature, so sqrt(401^2 – 105^2) = 387 nm.
[9] KAON 461, Table 1 for LGS mode with 10th magnitude TT star.
[10] KAON 461, Appendix 2 for LGS mode with 10th magnitude TT star.
[11] Performance decrease driven primarily by simplification to laser asterism and reduction in laser power.
[12] KAON 461, Table 1 for NGS 'bright star' performance.
[13] KAON 461, Appendix 1 for NGS mode with 8th magnitude TT star. Note, NGWFC should have similar performance, because the Keck 1 LGS upgrade will not affect NGS science performance.

requirements for certain science cases indirectly increased the difficulty of meeting the requirements in Table 1. Offsetting this, a calculation error was identified and corrected (§5.7), improving NGAO tip-tilt performance for high sky fraction science cases.

During the PD phase, these budgets were collated into three key spreadsheet documents:

- KAON 721, "Wavefront Error Budget Tool"
    - Containing Wavefront Error and Ensquared Energy Budgets
- KAON 722, "NGAO High-Contrast Error Budget Tool"
- KAON 723, "Performance Flowdown Budgets"
    - Containing transmission and background budgets, astrometric precision budget, observing efficiency and uptime budgets, and numerous supporting flow-down budgets such as non-common-path tip/tilt budget and non-correctable wavefront error budgets.

3.3 Wavefront Error Requirements Summary

The highest-level performance requirements for NGAO are documented in the Systems Requirements section of the NGAO Requirements Contour Database (see Appendix A), with the key requirement for wavefront and ensquared energy documented in SR-20, summarized in Table 2, and SR-21, which states

"The NGAO system shall produce a point spread function of a point source object with an ensquared energy of greater than or equal to 50% with a size of 70 mas as measured at the center of the science instrument focal plane for targets with a zenith angle of less than 5 degrees."

NGAO Key Science Case	High-order Wavefront Error (nm, RMS)	Tip-tilt Error (mas, RMS)	Effective Total RMS Wavefront Error (nm)	Science Pass-band	Strehl Ratio	Ensquared Energy within a 70 mas spaxel	Single-Integration Time (sec)
Galaxy Assembly	163	4.9	185	K	76%	74	1800
Nearby AGN's	163	4.7	181	Z	19%	26 w/in 34 mas	900
Galactic Center	190	2.2	193	H	58%	59	10
Exoplanets	162	3.8	174	H	64%	68	300
Minor Planets	164	4.7	181	K	77%	25	120
Io	115	2.1	117	K	89%	83	10

Table 2. High-level NGAO Wavefront Error Performance Requirements Summary from SR-20. High-order (HO) wavefront errors are errors with spatial frequencies higher than the tip-tilt (TT) error modes. The Effective Wavefront Error is the error that provides the same Strehl, through the Marechal approximation, as the produce of HO and TT Strehl ratios. EnsqE is within a 70 x 70 mas spaxel, except in the case of the Nearby AGN's science case, where the Z-band EnsqE estimate is given for a 34 x 34 mas spaxel.

Detailed description of the error budgets that support SR-20, and their basis, constitutes the majority of this report. The KAON 721 wavefront error budget tool is described in §16, an example detailed budget for the Galaxy Assembly case is provided in §6, and summary detailed budgets for the full suite of NGAO science cases are provided in Appendix A.

3.4 High-Contrast Requirements Summary

The highest-level image contrast requirement for NGAO is captured in SR-98, which states

"The NGAO system shall be able to detect point sources with brightness contrast as follows:

Separation	ΔH	ΔJ
0.1"	--	8.5 (goal = 11)
0.2"	10	11
1.0"	13	--

Table 3. High-level NGAO Contrast Requirements from SR-98.

SR-98 is traceable to KAON 455, Science Case Requirements Document, for two classes of observation: the ΔH requirements from companions to nearby (20-30 pc) stars and the ΔJ requirements from Jupiter analogues around T Tauri stars.

High-contrast performance estimates are maintained in a separate configuration controlled spreadsheet, KAON 722. Based upon a spreadsheet originally developed by B. Macintosh of LLNL in support of the GPI adaptive optics system, KAON 722 uses a spatio-temporal power spectrum model for each of several key AO system aberrations to evaluate the residual speckle and photon noise in the cleared-out 'dark hole' region surrounding an idealized AO coronagraphic PSF.

Due to the specialized nature of high-contrast observations, and the relative lack of detailed high-contrast performance simulations utilizing LGS (not to mention tomographic LGS) wavefront sensing, there are relatively few direct performance flow-down requirements. Most importantly, NGAO has made a design decision to sample and correct the telescope pupil with N = 60 subapertures spanning the 10.949 meter Keck Telescope maximum diameter, a decision driven not by our usual WFE optimization process (§5.3), but rather KAON 722 considerations. Specifically, we have maintained N = 60 in order to provide NGAO high spatial frequency control for speckle clearing over a large AO working angle. Strictly speaking, we have found NGAO WFE performance quite weakly dependent upon the exact choice of N ranging between N = 48 and N = 64, when bandwidth error (frame rate) reoptimization is performed. Compared to our SDR choice of N = 64, we subsequently revised our sampling baseline to N = 60 in order to manage known pupil nutation seen at the Keck Telescope Nasmyth platform.

During the NGAO DD phase, additional high-contrast modeling will be performed as part of the further refinement of the DAVINCI coronagraph design.

3.5 Astrometric Precision Requirements Summary

The highest-level astrometric precision requirement for NGAO is captured in SR-47, which states

“NGAO shall achieve an astrometric precision of 100 microarcseconds for observations taken with 120 seconds of each other and 250 microarcseconds for observations taken within 30 days.”

KAON 480 describes the key considerations for meeting the NGAO astrometric precision requirements, in both sparse field and crowded field science scenarios. During the PD phase, we expanded and organized an astrometric error budget and incorporated this into KAON 723, “Performance Flow-down Budgets”. Because of the research nature of understanding the root causes and limitations of astrometric variability of the current Keck II LGS AO system, it is difficult to make quantitative assessment of all factors potentially affecting NGAO astrometric precision. Still, using KAON 723 as a guide, we know that astrometric precision will be improved as wavefront error is reduced, particularly for crowded field science, such as the Galactic Center, where source confusion is thought to be among the major error sources.

One of the flow-down requirements from the astrometric precision budget (already implemented at Mauna Kea) is the installation of an active $C_n^2(h,t)$ monitor, which will provide turbulence structure and anisoplanatism information in support of post-observing data analyses, including anisoplanatic PSF estimation[14].

4 NGAO Science Cases

Science Case parameters for NGAO have been updated by Max and McGrath during the NGAO preliminary design phase (XXX Need KAON reference for this). The updated parameters are repeated here for convenience in Table 4.

Science Case Name	Zenith Angle (Deg)	Guide stars	NGS color	Required sky coverage (%)	Galactic latitude, |b| (deg)	Science Filter	Evaluation Filter	Max Single Exposure Time (Sec)	LGS/NGS	NGAO Key Science Case	Error Budget Case Name (if different then Science Case Name)	Applicable to NGAO (Yes/No)
Key Science Drivers												
Galaxy Assembly, e.g. Extended Groth S	30	Field Stars	M	30	≥60	Z, J, H, K	J, K	1800	LGS	Y		Key Science Driver
Nearby AGNs	30	Field Stars	M	30	≤60	Z, J, K	Z	900	LGS	Y		Key Science Driver
Galactic Center	50	IRS 7, 9, 12N	N/A	N/A	N/A	H, K	K	<10 (image) 900 (spectra)	LGS	Y		Key Science Driver
Exo-planets	30	Field Stars	M	30	≤30	J, H	H	300	LGS	Y		Key Science Driver
Minor Planets	30	Field Stars	M	30	≤60	Z	Z	120	LGS	Y		Key Science Driver
Science Drivers												
QSO Host Galaxies	30	Field Stars, possibly the science object	M/ A?	30	≤60	Z, J, H, K	K	900	LGS			Science Driver
Gravitational Lensing	30	Field Stars	M	30	≥60	I, Z, J, H, K	J, K	1800?	LGS			Science Driver
Astrometry Science	30	Field Stars	M	30	≤60	H, K	H	30 ?	LGS			Science Driver
Transients	30	Field Stars	M	30	40	Z, J, H, K	Z	900	LGS	N		Science Driver
Resolved Stellar Populations	50?	Field Stars	M?	30	?	I, K	I	300?	LGS			Science Driver
Debris Disks and Young Stellar Objects	30	Field Stars	M	30	≤30	I, Z, J, H	I	300	LGS			Science Driver
Size, Shape, and Composition of Minor P	30	Field Stars	M	30	≤60	I, Z, J	I	120	LGS			Science Driver
Gas Giant Planets		Satellites (non-sidereal)	G	N/A	N/A	J, H, K	K	2?	NGS?			Science Driver
Ice Giant Planets		Satellites (non-sidereal)	G	N/A	N/A	J, H, K	H	2?	LGS			Science Driver

Table 4. Science Cases Parameters for NGAO PD phase.

[14] Britton, M. C., “Analysis of crowded field adaptive optics image data,” in Advances in Adaptive Optics II. Edited by Ellerbroek, Brent L.; Bonaccini Calia, Domenico. Proc. SPIE, Volume 6272, July 2006.

These input parameters represent the observing scenario details developed via the process of Figure 1 and are the parameters that will be used in the summary evaluation of NGAO performance for all science cases in §8.

5 KAON 721, "Wavefront Error Budget Tool"

5.1 Introduction

NGAO performance The primary tool for the development and maintenance of the NGAO WFE budgets is a sophisticated Microsoft Excel spreadsheet (KAON 721) developed at Caltech by R. Dekany and collaborators over the past 10 years and significantly expanded for NGAO. It has been extensively validated against engineering error budgets maintained by Wizinowich, Neyman, and van Dam (§5.7.1), validated with detailed wave-optics Monte Carlo simulations (e.g. Arroyo, LAOS), and vetted against error budgets developed for TMT NFIRAOS (§5.7.2). It has also been anchored to observed on-sky performance of operational AO systems at Keck and Palomar Observatories.

KAON 721 supports the rapid evaluation of wavefront error budgets applicable to different AO systems / modes (e.g. Keck II NGS / LGS or NGAO NGS / LGS), different observing scenarios, typically designed to correspond to NGAO science cases, and different science instrument options (e.g. OSIRIS, DAVINCI).

The selection of WFS camera frame rates and off-axis NGS brightnesses and distances are typically optimized parameters that are found subject to constraints of necessary sky coverage fraction or guide star brightness, in the case of a known specific science target. Thus, each error budget for NGAO corresponding to each key science case, assumes operation at a slightly different frame rate[15].

Through a series of configuration worksheets, KAON 721 provides a detailed description of the parameters necessary to accurately model AO system performance:

- AO system architectures and design choices
- Atmospheric turbulence models
- Telescope parameters and as-built optical performance metrics
- WFS detector properties, such as quantum efficiency, dark current, and read noise
- Numerous adaptive optics error budget terms, specific to any of several distinct AO system architectures (e.g. SCAO, MCAO, MOAO) for both NGS and LGS guide star modes
- Atmospheric dispersion
- Calibration and systematic error terms, such as thermally induced non-common-path flexure
- Several astronomical stellar density models for the evaluation of AO sky coverage

The assumptions and impact of several of these quantities are described here in subsequent sections.

KAON 721 has been successfully applied for over 10 years of design and on-sky validation of AO system performance at Palomar Mountain, and is considered proprietary to Caltech Optical Observatories,

[15] A future revision to KAON 721 may support definable, selectable WFS frame rates, but this is not currently supported.

available for distribution within NGAO. Within the context of the NGAO project, specific validation activities for KAON 721 are described in §5.7.

In the following sections, we briefly describe the input parameters and underlying error term calculations and allocations that constitute the NGAO wavefront error performance budget within KAON 721.

5.2 "Input Summary" Sheet

The large majority of architectural and observational parameters used to define each system evaluation are captured on a single 'Input Summary' worksheet of the KAON 721 workbook. Certain of these parameters represent NGAO architecture choices, while others are design choices made within individual NGAO subsystems. Collectively, they begin the flowdown of the highest-level SR-20 performance requirements, a process continued in further detail in KAON 723.

During the DD phase, we intend to revise this sheet to even more clearly capture more of the parameters needed to describe AO system architecture, and maintain the configurations of each of the NGAO science cases, should they evolve.

Worksheet	Parameter	Current Parameter Value	Units		Galaxy Assembly	Nearby AGN	Gal Cen	Gal Cen Spectra	Exo-planets	Minor Planets	Io	QSO Host Galaxies	Gravitational Lensing	Astrometry Science	Transients	Resolved Stellar Populations	Debris Disks and YSOs	Gas Giant Planets	Ice Giant Planets
				0	Key	Key	Key	Key	Key	Key	Key	Driver	Driver	Driver	Driver	Driver	Driver	Driver	Driver
				0															
Telescope	Name	Keck																	
Atm	Declination																		
	Zenith Angle	30.0	deg		30	30	50	50	30	30	30	30	30	30	30	50	30	30	30
	Cn2(h) Model	Mauna Kea Ridge																	
	r0 at Zenith	0.160	m																
	Wind speed	9.5	m/s																
	Outer Scale	50	m																
HO Flux	Guide Star Spectral Type	NGS	(NGS/LGS)		LGS	LGS	LGS	LGS	LGS	LGS	NGS	LGS	LGS	LGS	LGS	LGS	LGS	LGS	NGS
	Guide Star Brightness	8.0	mV								5.0								8.0
	HOWFS NGS Spectral Type	G									G								G
	Num LGS Subaps Across	0																	
	Num NGS Subaps Across	60																	
	HO Integration time	0.00050	sec																
	HO WFS CCD Read Time	0.50	frame time(s)																
	HO RTC Compute Latency	0.00050	seconds																
	PnS RTC Compute Latency	0.00050	seconds																
	HOWFS Detector	CCID74																	
LGS Flux	Na Column Density	3E+09	atoms/cm^2	3E+09															
	Pulse Format	NGS																	
	Laser Power	NGS	Watts																
	Return Calculation Basis	Measured	(Measured/Theoretical)	Measured															
	Laser-thru-LLT Transmission	1.00																	
HO Cent	Num Pixels per Subap Across	4																	
	Pixel IFoV	1.6	arcsec																
	Range Gating?	0																	
	Intrinsic HOWFS GS diameter	3.9	arcsec		LGS	LGS	LGS	LGS	LGS	LGS	1.1	LGS	LGS	LGS	LGS	LGS	LGS	LGS	3.9
	Perfect Uplink AO?	0.00																	
	Aberrations in Uplink Beam	0.0	arcsec																
	LLT Off-axis Projection Distance	0.0	m																
	Use Max LGS Elongation in Calculation?	NO		NO															
	Downlink Aberrations	0.25	arcsec																
	Charge Diffusion	0.25	pixels																
	ADC in HOWFS?	NO																	
FA Tomo	Number of Laser Beacons	0																	
	LGS Beacon Height above Telescope	90	km																
	LGS Asterism Radius	0.00	arcmin																
	Single Laser Backproj FA Reduction Factor	1.0																	
Na H	Vertical Velocity of Na Layer	30.0	m/s	30.0															
Fit	Physical Actuator Pitch	0.0035	m																
Alias	Use Anti-aliasing in HOWFS?	YES																	
	Aliasing Reduction Factor	0.67		0.67															
Stroke	Number of Woofer Actuators Across Pupil	20																	
	Number of Tweeter Actuators Across Pupil	64																	
	Woofer Peak-to-Valley Stroke	4.0	microns																
	Tweeter Peak-to-Valley Stroke	1.3	microns																
	Woofer Interactuator Stroke	1.2	microns																
	Tweeter Interactuator Stroke	0.5	microns																
	Woofer Conjugate Height	0.0	meters																
	Tweeter Conjugate Height	0.0	meters																
	Static Surface Errors to be Corrected	1.0	microns																
Go-To	Science Mode	SCAO	(SCAO/MOAO/MCAO)																
Dig	Number of Controller Bits	16	bits																
TT Flux	TT Guide Star Brightness	8.0	mV				12.2	12.2	18.3		5.0						16.0	5.0	8.0
	TT NGS Spectral Type	G			M	M	IRS7	IRS7	M	M	G	M	M	M	M	M	M	G	G
	Subaperture Shape	circular	(circular/square)	circular															
	Num TT Sensors Used for TT	0																	
	Num TTFA Sensors Used for TT	0																	
	Num 3x3 Sensors Used for TT	0																	
	Num HOWFS Used for TT	1																	
	TT Integration Time	0.0005	sec																
	TT Compensation Mode	0	(SCAO/MOAO/MCAO/MOAO Point and Shoot,Indep PnS)																
	TT Detector	CCID74																	
TT Meas	TT Sensor Type	NGS	(Pyramid/SH)																
	TT Star Sharpened by AO?	NO																	
	Assume Fermenia TT Sharpening?	NO		NO															
	ADC in TT sensor?	NGS																	
	Num TT Pixels Across Subap	4																	
	TT Binning Factor	1																	
	TT Pixel IFoV	1.60	arcsec																
	Intrinsic TT GS diameter	3.9	arcsec								1.1								3.9
TWFS Flux	TWFS Guide Star Brightness	18.0	mV				12.2	12.2	18.3		5.0						16.0	5.0	8.0
	TWFS NGS Spectral Type	G			M	M	K	K	M	M	G	M	K	M	M	M	M	G	G
	Num TWFS Subaps Across	NGS																	
	Num TWFS Pixels Across Subap	NGS																	
	TWFS Integration Time	2.0000	sec																
	TWFS Compensation Mode	SCAO	(SCAO/MOAO/MCAO)																
	TWFS Pixel IFoV	1.60	arcsec																
	TWFS Detector	NGS																	
Bandwidth	Kappa	1.0																	
	HO Servo Decimation Factor	20																	
	TT Servo Decimation Factor	20																	
	Telescope Input TT Reduction Factor	0.50																	
	LGS Focus Sensor	N/A	(TWFS/TT)																
Aniso	Optimize LGS Off-pointing	NO		NO															
	HO GS to Target for Sci Aniso WFE	1.00	arcsec		1.0	1.0	1.0	2.0	1.0	0.0	0.5	1.0	5.0	5.0	1.0	5.0	1.0	5.0	1.0
	HO GS to TT GS for TT Aniso WFE	-1.00	arcsec				5.6	5.6	0.0		0.5						0.0	30.0	1.0
	TT GS to Target (for TT Anisoplanatism)	0.00	arcsec				5.6	5.6	0.0		0.5						0.0	30.0	1.0
	TWFS GS to Target (for Truth Anisoplanatism	0.00	arcsec				5.6	5.6	0.0		0.5						0.0	30.0	1.0
CA	CA Rejection Factor	NGS																	
Atm Dispersion	Science ADC?	YES																	
	Science Disperson Correction Factor	20		20															
Cal	Instrument	DAVINCI																	
	Uncorrectable AO System Aberrations	25	nm																
	Dynamic WFS Zero-point Calibration Error	20	nm																
	Leaky Integrator Zero-point Calibration Error	10	nm																
	DM-to-lenslet Misregistration Errors	15	nm																
	DM-to-lenslet Scale Errors	10	nm																
Margins	High Order Wavefront Error Margin	45	nm																
	Tip-tilt Error Margin	2.0	mas																
Sky Coverage	TT Star Density Model	Spagna		Spagna															
	Required Sky Coverage Fraction	N/A			30%	30%	N/A	N/A	30%	30%	NGS	N/A	30%	30%	30%	30%	30%	N/A	N/A
	TWFS Star Density Model	Bachall		Bachall															
	Required TWFS Sky Coverage Fraction	N/A																	
	Galactic Latitude, b	N/A	deg		60	60	0	0	30	60	N/A	60	60	60	40	60	30	N/A	N/A
Science Filter	Primary Science Filter	H			K	Z	H	H	H	Z	Z	H	H	H	Z	I'	I'	K	H
	Max Science Exposure Time	2	sec		1800	900	10	900	300	120	10	900	1800	30	900	300	300	2	2
Worksheet	Parameter	Current Parameter Value	Units		Galaxy Assembly	Nearby AGN	Gal Cen	Gal Cen Spectra	Exo-planets	Minor Planets	Io	QSO Host Galaxies	Gravitational Lensing	Astrometry Science	Transients	Resolved Stellar Populations	Debris Disks and YSOs	Gas Giant Planets	Ice Giant Planets

Table 5. KAON 721 "Input Summary" worksheet, configured for NGAO LGS mode observing and the Galaxy Assembly key science case. Red fields indicate entries that may be affected by optimizations. Red typeface indicates observing scenarios needing NGAO NGS mode.

The terms in Table 5 are largely self-explanatory, although their quantitative implementation requires reference to KAON 721 itself. All the same, a few items are worthy of additional explanation here:

- **HO Flux, Number of Subapertures Across**: NGAO has high-order wavefront sensors designed to sample the telescope pupil with ~60 subapertures across the 10.949 m maximum diameter.

Our WFS's, however, are designed for 63 x 63 subaperture format (e.g. oversizing the pupil somewhat) to handle known pupil nutation in the Keck telescopes. See Keck Drawing 1410-CM0010 for more detail.

- **HO Flux, HO WFS CCD Read Time** is currently given as a fraction of the HO WFS frame rate, which is typically an optimization variable. In the future, this will be replaced with an amplifier dwell time or equivalent parameter to specify the detector read time.
- **LGS Flux, Na Column Density** of 3 x 10^9 atoms/cm^2 is below median density (approximately 25^{th} percentile). See Figure XXX for a trade study of performance vs. sodium density.
- **TT Flux, TT Compensation Mode** is a complex choice that supports traditional single-conjugate AO correction, MCAO, single-LGS MOAO correction, and multiple patrolling LGS (aka 'Point and Shoot') architectures. Changes to this parameter must be carefully understood by the KAON 721 user.
- **Atm Dispersion, Science Dispersion Corrector Factor** uses a crude multiplicative (divisive, actually) factor to estimate the residual performance, if a science ADC is used. In the future, KAON 721 will allow for definition of more realistic, design-informed residual dispersion.
- **Margins** (e.g. performance margins) are held apart from physical error terms and constitute the difference between use of KAON 721 as an error budget (including margins) and as a performance prediction or system diagnostic tool (assuming margins are not invoked.)

[XXX – more to do; need feedback on the least obvious of the Input Summary entries].

5.3 Optimization ("Optim") Sheet

Error budgets are summarized on the 'Optim' worksheet, as this is location of the optimization parameters. (Optim is commonly used for the generation of trade study results, as well.) Separate error budgets are maintained for the science path, the sharpening of field TT stars, and for the wavefront error residual sensed by the TWFS (if applicable). For patrolling LGS TT sharpening systems, the camera frame rates of corresponding HO LGS WFS's are separately optimized. Additional description of this tool is provided in Appendix C (XXX verify).

5.4 Encircled / Ensquared Energy ("EE") Sheet

KAON 721 employs a multi-halo model to estimate the encircled or ensquared energy in the NGAO PSF. The intent is to approximately model the effect of residual wavefront errors of different spatial frequency. For example, residual tip-tilt errors are treated as a convolution of the diffraction-limited PSF with residual TT errors, while high-order WFS measurement error results in light scattered to high spatial frequencies as it manifests as random noise on the HODM surface. Five different width Gaussians contribute to the PSF model:

- Diffraction-limited, convolved with TT errors
- ½x the seeing-limited width (containing low spatial frequency errors, such as focus errors due to sodium height variations)
- A variable-width PSF for focal anisoplanatism (for which the width of the component is a function of the focal anisoplanatism coherence parameter, d_0)

- 1x the seeing-limited width (containing most atmospheric residual errors)
- 2x the seeing-limited width (containing measurement error, scintillation, and uncorrectable telescope, AO, and instrument errors.)

The power in each component is calculated assuming 1) the DL component has the fraction of energy represented by the Strehl ratio (at the observing wavelength), 2) the remaining fraction of energy (1-SR) is allocated into each of the four remaining components based on the relative power of the corresponding error terms (e.g. allocated by wavefront variance). A check is made to ensure the sum of all PSF components is appropriately normalized.

KAON 721 also provides seeing-limited encircled / ensquared calculations for comparison purposes.

5.5 Wavefront Error Budget Terms

5.5.1 High-order Wavefront Errors

5.5.1.1 Atmospheric Fitting Error

We use the standard model for fitting error,

$$\sigma_{Fitting} = \left(\frac{500}{2\pi}\right)\sqrt{a_F\left(\frac{\Delta x}{r_0}\right)^{\frac{5}{3}}}\ \mathrm{nm}$$

Where a_F = 0.28 assuming a continuous facesheet, pyramidal DM influence function.

5.5.1.2 Bandwidth Error

During the PD phase, we have implemented the bandwidth servo error model described in detail in KAON 710, which is based upon a Fourier domain analysis of the 'open-loop' go-to control law in a discrete time system. From Equation 13 of KAON 710,

$$\sigma_{Bandwidth} = \left(\frac{500}{2\pi}\right)\ \sqrt{\zeta[\alpha]\left(\frac{vT}{r_0}\right)^{\frac{5}{3}}}\ \mathrm{nm}$$

Where $\zeta[\alpha]$ is the open-loop normalized variance numerically derived to be,

$$\zeta[\alpha] = 5.57\ \alpha^2 + 25.125\ \alpha + 11.38$$

where $\alpha = \tau_c/T$ is the delay parameter describing the compute delay t_C in units of frame time T, and v = turbulence-weighted wind velocity and T the WFS frame time.

5.5.1.3 High-order Measurement Error

High-order wavefront measurement error is perhaps the most complicated of the calculations supported in KAON 721. For our purpose here, it will suffice to describe the error as,

$$\sigma_{Measurement} = \left(\frac{500}{2\pi}\right) \mathrm{E_P} \; \frac{\pi}{8\ \mathrm{SNR}} \sqrt{\left(\frac{3}{2} FWHM\_subap\right)^2 + \theta^2}\ \mathrm{nm}$$

Where E_p = 0.1902 + 0.1067*ln(N^1) based on Hardy, Table 8.2, pg 276 (see also Eqn 9.58, pg 342) is the reconstructor error propagator between centroid error and error of the wavefront reconstructed in the pupil plane for each measurement. SNR is the signal-to-noise ratio of the subaperture detection and includes the following physical effects:

- Guide star flux (sodium LGS or NGS)
  - Based upon measured LGS return data reported from SOR as extrapolated to Mauna Kea's latitude, magnetic field direction, measured (Hakeakala) seasonal sodium abundance, LGS distance, atmospheric extinction
  - Thus, we assume 100 photons/cm^2/sec/W coupling efficiency, where W are Watts of laser power delivered to the mesosphere and photons are measured above the Earth's atmosphere on the downlink, and a sodium column density of 3 x 10^9 atoms/cm^2.
- NGS stellar spectral type, if applicable
- WFS exposure time
  - Typically assuming 100% shutter efficiency
- System transmission for each WFS path, including any band-defining filters
  - Using detailed coating models, including coating degradation and dirt (scatter) losses for each surface, depending on its local atmospheric environment
  - Including transmission contingency of 3% held at the system level (to be allocated should acceptance testing of coating data miss the mark, particularly for long lead items).
- Detector QE, read noise, dark current
  - Based on measured data of noise vs. frame (readout) rate for each type of WFS CCD camera under consideration
  - This is typically 2.2 e- read noise for the CCID74 when operating at 1,000 fps
- Fratricide noise
  - Implemented in a pupil-average sense of contributing additional 'background' noise, calculated from Rayleigh scatter lidar equations. In this case the statistics depend both on Poisson noise and assumptions about the fluctuations in Rayleigh background and the cadence of LGS WFS de-tuning to re-measure the WFS background.
- Sky background in the observing band of the sensor
  - Based on the physical instantaneous field of view (IFoV) of the WFS pixel or binned super-pixel, whichever is appropriate.
- Phase of the moon, as a contributor to scattered light
- The effective servo loop gain, which considers the contribution from photons collected during a -3db time, not just that collected during a single WFS exposure time.

And $FWHM_{subap}$ is the full-width-at-half-maximum of the subaperture WFS image, which is calculated taking into account the following physics, most of which generate specific functional requirements through the performance budget flowdown:

- Subaperture diffraction in the WFS observing band
- NGS size
  - Intrinsic size of the guide star
  - Tip-tilt removed atmospheric seeing on the downlink
  - Atmospheric dispersion across the WFS band
  - Any dispersion correction
- Or, LGS size
  - Laser beam image quality
  - Beam transfer optics quality
  - Tip-tilt removed uplink atmospheric aberrations over the projector aperture
  - Any higher-order uplink pre-compensation
  - Off-axis LGS perspective elongation
  - Tip-tilt removed atmospheric seeing on the downlink
  - WFS detector charge diffusion (including any binning effects)
- Uncorrectable aberrations in the telescope and AO system

Built upon these principles, we typically estimate the FWHM of the LGS spot to be 1.27 arcsec (average over the telescope aperture).

Furthermore, KAON 721 calculates measurement noise independently in LGS mode for both the fixed laser asterism and the patrolling laser asterism, which are allowed to run at different frame rates in order to optimize system performance.

5.5.1.4 LGS Tomography Error

KAON 721 captures in a parametric fashion the fundamental results of detailed Monte Carlo wavefront optics propagation modeling conducted with LAOS and two independent codes developed by R. Flicker and D. Gavel. The results of some of these tomographic analyses are documented in KAON 429, "LGS asterism geometry and size" and KAON 492, "NGAO null-mode and quadratic mode tomography error". Based on these studies, we found the key determinant to estimating the null-mode corrected tomography error to be the areal density of LGS beacons on the sky. Secondary to this, the specific distribution of LGS on sky had relatively minor impact, resulting in small azimuthal field-dependent errors over our small NGAO FoV.

A detailed validation comparison of our different codes is described in KAON 475, "Tomography Codes Comparison and Validation for NGAO" as well as indirectly within KAON 629, "Error budget comparison with NFIRAOS".

Our choice of LGS fixed asterism (a triangle on 10 arcsec radius plus a central LGS), results in a predicted, null-mode corrected tomography error of 37 nm RMS. We achieve this assuming null-mode correction based upon the use of 2 tip-tilt and 1 tip-tilt-focus-astigmatism NGS, that are themselves sharpened by the patrolling LGS + LO WFS AO subsystems, as described in KAON 492.

Because these wave-optics-based performance estimates were used primarily in the design process of the fixed LGS asterism, we intend to conduct further simulation-based analysis of our selected asterism (for e.g. more robust understanding of zenith angle dependency) in the DD phase.

5.5.1.5 Multispectral Error

The wavefront error that arises from wavefront sensing in a different band than the science band is known as multispectral error. It arises from differential atmospheric refraction of the two beams, resulting in the sensor light following a slightly displaced path through the Earth's atmosphere. A quantitative model of this error as a function of zenith angle and wavelength difference, provided by Hardy (Ch. 9.3.4, pg 325) and is coded into KAON 721.

5.5.1.6 Uncorrectable Static Telescope Aberrations

Flicker and Neyman reported on the ability of NGAO to correct for measured Keck telescope segment map aberrations in KAONs 469, "Effect of Keck Segment Figure Errors on Keck AO Performance" and 482, "Keck Telescope Wavefront Error Trade Study". That model is encoded in KAON 721, and predicts a residual of 42 nm RMS, one of the largest error terms in the budget. Static errors in the Keck primary tend to hold up our choice of actuator density (N=60 across the pupil) to higher density than we might otherwise choose based on atmospheric fitting error (§5.5.1.1) alone.

5.5.1.7 Uncorrectable Dynamic Telescope Aberrations

Dynamically changing Keck telescope aberrations (e.g. segment vibrations, excluding a global pointing jitter handled in §5.5.2.2) are allocated 25 nm RMS in the NGAO error budget. This is a rather uncertain number, however, and is based upon private communications with the primary mirror phasing team (Chanan and Troy). More detailed analysis of the dynamical ability of NGAO to reject mirror segment vibrations is planned for the DD phase.

5.5.1.8 Static WFS Zero-point Calibration Error

We define static WFS zero-point calibration error as the residual wavefront error in the science beam at the completion of an internal NGAO wavefront calibration procedure. This 'flattening' of the science wavefront is typically limited by SNR in the calibration signal itself, for example using phase diversity techniques, or in stability of the system during a calibration routine.

Because zero-point (sometimes called 'centroid offset') calibration of the wavefront sensors includes error that are both inside and outside the spatial control bandwidth, we usually refer to the zero-point error as the error that could be correctable by the system DM, if it had better information. The wavefront errors that are uncorrectable by NGAO are allocated separately for the AO System (§5.5.1.14) and DAVINCI (§5.5.1.15).

5.5.1.9 Dynamic WFS Zero-point Calibration Error

Changes in the size and shape of the HO WFS subaperture PSF can result in a systematic error in the science wavefront. As subaperture PSF varies, non-linearities in the WFS slope response function results in changes to the local wavefront shape for the same zero-point (aka centroid offset). This was a major limitation to the performance of the original Keck AO system[16].

NGAO strategy is to induce a known, small amplitude tip-tilt signal (known as a small amplitude dither) into the beam, from which the changes in the slope response curve can be extracted through wavefront sensor telemetry analysis. Still, this process will be imperfect, so we allocate 25 nm RMS wavefront error for the residual dynamic changes in WFS zero-point.

5.5.1.10 Stale Reconstructor Error

Our architecture choice for the optical relay, including image stabilization with a K-mirror, results in the constant rotation of the image of the telescope stop on the LODM and other NGAO internal pupils. Because the illumination pattern is changing with time, the RTC reconstructor will need to be periodically updated to maintain top performance. Similarly, the tomographic fixed asterism reconstructor will need to be periodically updated to take into account changes in the turbulence profile and strength.

The NGAO error budget makes an allocation for the wavefront error due to an out-dated or 'stale' reconstructor of 15 nm RMS. The implication of this allocation to the interface to the Keck $C_n^2(h,t)$ monitor and load times for new reconstructors in the RTC will be detailed in the DD phase. A study of the effect of rapid field rotation near zenith on the NGAO K-mirror was made in KAON 708, Limit to AO Observations from Altitude-Azimuth Telescope Mounts.

5.5.1.11 DM Finite Stroke Error

The NGAO architecture includes both LODM and HODM elements, increasing the available physical stroke for AO correction compared to the current Keck AO systems. Still, in poor seeing it becomes possible to saturate DM actuator stroke on one or the other of the mirrors.

KAON 721 models this effect crudely by estimating in a statistical sense the expectation value of the number of saturated actuators at a given time (assuming Gaussian statistics based on the RMS wavefront error). If, for example, 1% of the actuators are expected to saturate, we then assume the impact to the wavefront error budget is equivalent to an RMS wavefront error that reduces the Strehl ratio in the observing band by a factor of 0.99. Obviously, this is a crude model and even then more applicable to Strehl than EnsqE and EncE calculation (and not at all to high-contrast calculations). Still, for NGAO we rarely find ourselves concerned about finite stroke errors.

5.5.1.12 High-order Wavefront Aliasing Error

High spatial frequency wavefront aberrations above the Nyquist limit of our Shack-Hartmann NGS and LGS wavefront sensors can become aliased to appear incorrectly as low spatial frequency errors, which are then incorrectly imparted by the LODM onto the science beam.

KAON 721 includes the wavefront aliasing error proposed by Rigaut, Veran, and Lai (XXX) and supports a user-definable switch to reduce the amount of aliasing error if anti-aliasing stops are deployed in WFS's.

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[16] van Dam, et al., "The W. M. Keck Observatory Laser Guide Star Adaptive Optics System: Performance Characterization," *PASP* 118:310-318, 2006.

For NGAO, we have elected not to include an anti-aliasing spatial filter in the LGS WFS, because relatively extended subaperture spot size precludes effective spatial filtering. In the NGS WFS, we have not included an anti-aliasing spatial filter to reduce costs. High-contrast science using NGS WFS on bright stars will be hampered by this decision, but this was not deemed to be a key science case for NGAO.

5.5.1.13 Go-to Control Errors

The NGAO science path correction architecture is based upon the expected efficacy of go-to HODM control. KAON 721 allocates a total of 30 nm RMS wavefront error to effects specific to go-to control. KAON 723 flows this error down into the following terms:

- Incorrect measurement of LODM
  - Go-to control relies upon successful knowledge of the state of the LODM. This allocation levels requirements on LODM position knowledge that will be further explored in the DD phase.
- Incorrect calibration of LGS WFS
  - Residual non-linearities in the LGS WFS will corrupt the wavefront measurement which is then applied to the HODM. In a traditional closed-loop AO system, this error would be sensed and corrected in subsequent loop updates, but for NGAO we must know the true wavefront shape accurately.
- Geometric uncertainties
  - Non-uniform WFS subaperture of HODM actuator spacing may induce science wavefront errors separate from pupil registration errors between WFS's and DM's accounted for in §5.5.1.16.
- Incorrect actuation of MEMS DM's
  - The difference between commanded actuator position and actual position arrived at by a HODM actuator (as validated on the VILLAGES testbed.)

5.5.1.14 Uncorrectable AO System Aberrations

Internal AO system aberrations outside the spatial bandwidth of the HODM, or those imparted by optics removed from a system pupil, can induce uncorrectable AO system aberrations. KAON 721 allocates 33 nm RMS wavefront error to all uncorrectable AO system aberrations, while KAON 723 flows this error down onto specific surface quality requirements for each of the NGAO optics.

5.5.1.15 Uncorrectable Instrument Aberrations

Internal instrument aberrations that are outside the spatial bandwidth of the HODM, or are field dependent, cannot be corrected by NGAO. KAON 721 allocates 30 nm RMS to uncorrectable instrument aberrations for DAVINCI on-axis and 60 nm RMS at the edge of a 20 arcsec radius FoV.

5.5.1.16 DM-to-lenslet Pupil Mapping Errors

NGAO has a complex set of WFS and DM pupil mapping requirements. KAON 721 makes a high-level allocation of 21 nm RMS in the fixed LGS asterism path and 28 nm RMS in the patrolling LGS asterism path. During the PD phase, we elaborated upon this in KAON 723, flowing sub-allocations of this error with increasing detail. Evaluation of each possible registration error, however, proved too expensive in terms of computational and human effort for the PD phase. As a working estimate, we adopted a general tolerance that actuator and lenslet pupils should all be set and remain registered to the LODM (an adopted pupil fiducial) to less than 5% of the smallest subaperture spacing. Thus, for PD, engineering choices like the thermal stability within the cold enclosure (+/- 1C) are based on requiring 5% of a 1/60th aperture = 1/1200 of the pupil. The working tolerance was based on the collective experience of the NGAO team in having fielded numerous AO systems with typically 10% of a 1/20 pupil subaperture, including performance degradation experience for systems having pupil misregistration flexure. Our judgment was that for NGAO, a factor of 6 tighter tolerance would be sufficient to meet the 21 nm residual wavefront allocation. KAON 704, Opto-mechanical Registration Tolerances for "go-to" Adaptive Optics explores this tolerance in more detail.

In the DD phase, we will seek to confirm this experiential evidence and perform more detailed Monte Carlo analysis of NGAO pupil misregistrations. To save costs, we intended to make random misregisration draws from probability distributions built with our registration tolerances, and perform only forward performance evaluations (e.g. we do not intend to calculate sensitivity matrices for each pupil parameter within NGAO.)

5.5.1.17 Angular Anisoplanatism

As a singly-conjugated AO system, NGAO performance will fall as a function of normal angular anisoplanatism (Hardy Ch. 3.7.2, pg 102). KAON 721 encodes angular anisoplanatism error as a function of the field radius (1/2 the FoV) of each specific NGAO science case (thus, our WFE's are already the worst case for the science case described.)

Our calculation of θ_0, the angular coherence parameter, takes into account the finite Keck aperture, so is somewhat increased relative to the usually assumed infinite aperture isoplanatic angle.

5.5.1.18 High-order Wavefront Error Margin

To account for unforeseen sources of residual high-order wavefront error, we include in the NGAO error budgets a margin of 45 nm RMS, which is added in quadrature to the known, estimable errors. During DD phase, we reserve the option to allocate some or all of this error through revisions to the performance flowdown.

5.5.1.19 Other High-order Wavefront Errors

Additional high-order wavefront errors are carried in the NGAO error budgets, but due to their relatively small magnitude, we will only refer to them here as:

- Asterism Deformation Error
- Chromatic Error
- Dispersion Displacement Error
- Scintillation Error
- WFS Scintillation Error
- DM Hysteresis Error
- DM Drive Digitization Error

An interested reader is invited to review the implementation of these error terms in KAON 721. Note, some of these errors are simple allocations for the PD phase.

5.5.2 Tip-tilt Wavefront Errors

5.5.2.1 Tip-tilt Bandwidth Error

KAON 721 assumes a traditional single-pole model of tip-tilt bandwidth error,

$$\sigma_{TT\ Bandwidth} = \left(\frac{\mathrm{f_T}}{\mathrm{f_{-3db}}}\right)\left(\frac{\lambda}{D}\right)\sqrt{\cos(\zeta)}\ arcsec$$

Where f_T is the effective tilt tracking frequency (Hardy, Eqn. 9.64, pg 345), evaluated at the observing zenith angle, ζ, and f_{-3db} is the tilt servo rejection bandwidth. Typically, we evaluate at λ = 500 nm, to find f_T ~ 1.2 Hz at ζ = 30 deg, after applying a correction for the impact of our Keck-assumed L_0 = 50 m outer scale of turbulence (compare Hardy Eqn. 7.63, pg 255 and Eqn. 9.8, pg 315).

5.5.2.2 Residual Telescope Pointing Jitter Error

The Keck Telescopes have a well known pointing jitter oscillation that, without additional consideration, would limit the ability of NGAO to meet its science goals. KAON 680, "Vibration Mitigation" considers this effect in detail. KAON 721 assumes the successful mitigation of pointing jitter using one or more of these mitigations to an input disturbance level of only 1 milliarcsec RMS, a factor of between 10x and 20x improvement over the telescope jitter seen with the current Keck AO system (KAON 680). Because this jitter is observed at high temporal frequency (typically 29 Hz), the regular NGAO tip-tilt rejection loop is limited in its corrective ability. Thus, any shortfall in our control of input jitter will map directly to NGAO performance, particularly for high-sky-coverage science programs, where NGS photon scarcity precludes high-bandwidth operation. As can be seen from Table 2, our final tip-tilt error requirements are of the order of 3-5 milliarcsecond residual one-axis tip-tilt error, so any failure to control input jitter to at least this level would have a significant impact on performance.

5.5.2.3 Tip-tilt Measurement Error

Tip-tilt measurement error is calculated based upon the number and type of wavefront sensor used for tip-tilt sensing. For NGAO, there are three distinct modes of tip-tilt sensing: with the LO WFS at IR wavelengths, with the NGS WFS in 5x5 subapertures while operating in LGS mode, and with the NGS WFS in 60 x 60 mode while operating in NGS mode. In each of these cases, we use the same measurement error equation at in §5.5.1.3, omitting the error propagator term, E_p.

SNR calculations for TT sensing include the same physical effects as for high-order wavefront sensing. However, because we frequently use near-infrared wavelengths for tip-tilt, we have to be careful to consider the impact of thermal noise background, which is a function of the architecture of the specific wavefront sensor (for example, the inclusion of a cold stop is typically used to limit thermal irradiance).

For the NGAO LO WFS, which utilizes between 1 and 3 NGS for tip-tilt sensing, we calculate the measurement error in ensemble, forming the signal from the total photoflux from 1, 2, or 3 stars (whose brightnesses are related to the sky coverage calculation described in XXX) and the noise term from all the noise sources across all tip-tilt sensors. Thus, we add up all the pixels in the tip-tilt measurement, for example, which in the case of 2 TT + 1 TTFA sensors, sampled with 2x2 pixels per subimage, would equal 2 * (2x2) + 1 * 4 * (2x2) = 20 pixels, where the TTFA is assumed to be a 2x2 subaperture Shack-Hartmann sensor. Thus, the total flux from 3 stars, and noise (and background, etc.) from 20 pixels are included in the tip-tilt measurement error calculation.

KAON 721 currently does not support the inclusion of thermal background noise between near-infrared bands (e.g. between J and H atmospheric bands). Although we have considered a LO WFS filter combination that blocks the inter-band OH emissions as a design choice, in the DD phase we will confirm the need or non-need for this complication based on cost and the impact of these additional sky noise photons.

Tip-tilt measurements made with the NGS WFS are more straightforward, using the same options as described in §5.5.1.3, independent of choices made for the HO WFS. In the LGS observing mode where the science target itself is used for both tip-tilt and blind mode measurement, NGAO has the additional benefit of suffering no tip-tilt anisoplanatism. KAON 721 supports an intermediate method of calculating partially corrected visible light PSF's within the relatively large 5x5 (~2.2 meter diameter) subapertures, following the analysis of Femenia (REF XXX), but this is not invoked for NGAO.

5.5.2.4 Tip-tilt Anisoplanatism Error

The tip-tilt error measured by an off-axis NGS will differ from that appropriate for an on-axis science target. This TT anisoplanatism is described quantitatively by Hardy (Ch. 7.4.2, pg 250).

In the case of NGAO, where we will employ multiple NGS for TT measurement, we assume a reduction in TT anisoplanatism, based upon the likely reduction in nearest-neighbor distance in a random star field. For N = 2 TT stars, KAON 721 assumes the effective NGS off-axis distance is 0.67 times the distance of the brighter NGS, while for N=3 the effective off-axis distance is 0.53 times this amount. This is conceptually equivalent to the idea of using TT measurement averaging to reduce TT anisoplanatism, but does not include more detailed considerations, such as optimal TT estimation based upon NGS off-axis distance, SNR, color similarity to the science target, etc.

In the DD phase, we will consider the cost/benefit of further expanding this TT averaging analysis using more detailed wave-optics simulations.

5.5.2.5 Centroid Anisoplanatism Error

Dekens[17] describes the effect of aliasing of coma and other higher-order wavefront errors as an apparent (and incorrect) TT residual error. This was a source of concern at the PDR for the original Keck AO system, as the calculated effect was considerable. Actual Keck AO experience has shown, however, that the worrisome magnitude of centroid anisoplanatism error was not realized. It has been postulated that the effects of finite integration time averaging or finite servo bandwidth mitigate this effect to some level (P. Wizinowich, private communication), but a reliable post-mortem analysis of centroid anisoplanatism in the current Keck AO system has not been performed.

[17] Dekens, F. "Atmospheric characterization for adaptive optics at the W. M. Keck and Hale telescopes," PhD thesis, UCI, 1999.

KAON 721 allocates 0.55 milliarcseconds of CA error, a factor of 20 reduction over the predictions by Dekens which are known to be overly pessimistic.

This remains perhaps the most uncertain term in the TT error budget and will be further considered in the DD phase. We have not agreed upon a more detailed analysis approach, but will consider the applicability of detailed LAOS simulations to better understanding this issue.

5.5.2.6 Atmospheric Dispersion Error

Maintaining small image size in the science path requires excellent correction of atmospheric dispersion errors. KAON 721 currently handles ADC improvement over inherent atmospheric dispersion as providing a factor of 20x improvement (and so this is a function of observing band). During DD phase, we will replace this model with one based upon the performance of our actual ADC design, appropriate to each observing band.

5.5.2.7 Non-common Path Tip-tilt Errors

Residual thermal flexure between the science instruments and the sensors providing TT information (the LO WFS in LGS mode, or the NGS WFS in NGS mode) will lead to blurring of the AO PSF. KAON 721 allocates for non-common-path TT errors a value of 3.2 mas / hr, which KAON 723 flows down into items such as thermal stability of the NGAO optical bench, thermal stability interior to the LOWFS, etc.

5.5.2.8 Tip-tilt Error Margin

To account for unforeseen sources of residual tip-tilt error, we include in the NGAO error budgets a margin of 2.0 milliarcseconds. During DD phase, we reserve the option to allocate some or all of this error through revisions to the performance flowdown.

5.5.3 Tip-tilt Sharpening Budget

KAON 721 includes a separate high-order wavefront error budget for the patrolling LGS-based AO system used to sharpening NGS in the LO WFS. The NGAO architecture calls for asynchronous operation of the combined patrolling LGS / LO WFS DM correction subsystem, allowing for independent optimization of key sharpening budget parameters, such as the amount of laser power dedicated to each patrolling LGS and the frame rate of the patrolling LGS WFS's.

The performance benefit of go-to control sharpening of TT NGS was reported upon in Dekany, 2008 (XXX), from which the NGAO project justified the additional expense and complexity of a TT sharpening system. As part of the Build-to-Cost project rescope (see KAON 642), the NGAO team looked closely at the science priorities and the cost/benefit of numerous design options, and elected to retain the TT sharpening subsystem based upon the high priority given to wide-sky-fraction operation of NGAO.

5.5.4 Truth WFS Budget

KAON 721 contains a separate error budget to estimate the fidelity with which the visible TWFS can measure slow variations in the correction calibrations. The TWFS budget includes consideration of the measurement error, the bandwidth error, atmospheric averaging, and other details to determine the residual error for each TWFS measurement.

During PD phase, we concentrated on the focus error component tracked by the TWFS, but have not had the opportunity to fully understand TWFS performance on other wavefront modes. In part, we expect our strategy of small amplitude TT dithering for LGS WFS gain calibration, to help mitigate the relatively large contribution of 'input' wavefront error that must be sensed with the TWFS in the current Keck AO system.

5.6 "Sky Coverage" Sheet

KAON 721 provides a number of optionally selectable star density models with which to calculate sky coverage fraction. NGAO calculations are made using the near-IR stellar density models from Spagna, which is parameterized by galactic latitude.

Our approach to multiple guide star TT performance is to 1) determine the off-axis distance and brightness of NGS that satisfies the NGAO science case's proscribed sky coverage fraction, 2) determine the brightness of other NGS in the field that are 'highly likely' to be found closer to the science target than the initial star, 3) repeat for a third star, 4) use the sum of photofluxes from all three stars to determine TT measurement errors. Using this approach, we find statistically that for a 'brightest star' brightness of V = 18 at off-axis distance R, the brightest star highly likely to be interior to a circle of radius R will be 0.28 times as bright (e.g. V = 19.3), and the 3rd star within the circle of radius R will be 0.135 times as bright as the original (e.g. V = 20.2).

Infrared star density models based on more complete and more recent publications, such as that described by Robin et al.[18] exist, and integration of these models into KAON 721 is noted as an area for future implementation (see §5.7)

5.7 Wavefront Error Budget Validation

5.7.1 Keck II LGS Performance Validation

To gain specific confidence in the fidelity of KAON 721 when applied to NGAO, an SDR trade study was performed using KAON 721 to model both the existing performance of the Keck 2 AO system and replicate the predictions for Keck 1 LGS made by Keck Observatory staff. This study, KAON 461, "Wavefront Error Budget Predictions & Measured Performance for Current & Upgraded Keck AO" fundamentally validated the simulation- and analysis-based engineering approach of KAON 721. Comparisons were made for each of:

- NGS mode performance (V = 8)
- LGS mode performance with bright NGS tip-tilt star (V = 10)
- LGS mode performance with faint NGS tip-tilt star (V = 18)

Although a strict quantitative term-by-term comparison of terms was difficult (due to uncertainties in knowledge of the 'on-sky' atmospheric $C_n^2(h)$ profile, which effects e.g. isoplanatic angle, both the overall budget predictions and the trends were consistent in all cases.

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[18] Robin, A. C., Reylé, C., Derrièrre, S., and Picaud, S., "A synthetic view on structure and evolution of the Milky Way", 2003, Astron. Astrophys., 409:523 (erratum: 2004, Astron. Astrophys., 416:157).

5.7.2 Comparison of NGAO and NFIRAOS Error Budgets

One of the recommendations of the SDR review panel was to also undertake a detailed error budget comparison between the Keck NGAO and TMT NFIRAOS AO systems. This study, KAON 629, "Error Budget Comparison with NFIRAOS", systematically accounted for differences in the AO architecture (science path go-to AO augmented with dual AO LO WFS sharpening for NGAO and multi-conjugate AO for NFIRAOS) and compared the two team's performance analyses on an equal input basis.

The most significant finding for the NGAO budget was the (known) double counting of certain high-frequency error terms that arise from independent evaluation of engineering budget models. Specifically, high-spatial-frequency errors counted as fitting error (§5.5.1.1) is also counted as a spatial frequency component of bandwidth error (§5.5.1.2). The assumption of error term independence is indeed a compromise made in the KAON 721 formalism. However, it tends to be a conservative one in that it tends to modestly underestimate system performance (thus, can be seen as another source of performance margin.)

Similarly, the KAON 629 highlighted the fundamentally different approach to sky coverage estimation between the two projects. While NGAO follows the approach described in §5.6, NFIRAOS uses a Monte-Carlo strategy of generating a large pool of candidate NGS asterisms in a field and evaluating the low-order 'blind mode' compensation and residual tip-tilt errors in order to estimate a median (or Nth percentile) probability of system performance as a function of galactic latitude.

The two approaches were directly compared earlier in the NGAO SD phase in KAON 470, "Keck NGAO sky coverage modeling". In that report, the approaches were found to be essentially equivalent in their conclusion for NGAO performance, although the more detailed Monte-Carlo technique was shown to provide more information on the source of residual errors than the (more computationally efficient) engineering spreadsheet model. It is interesting to note that during subsequent analysis of the KAON 721 during the PD phase, Chris Neyman uncovered a numerical 'factor of two' error in the implementation of the Spagna star density model that was not uncovered by the earlier KAON 470, but that upon reoptimization of tip-tilt NGS off-axis distance, brightness, and LO WFS frame rate (which is also noise dependent) resulted in only a modest revision to sky coverage performance, which presumably masked the effect during the KAON 470 study.

Overall, when normalized to equivalent input parameters, the NGAO and NFIRAOS error budget approaches were in KAON 629 demonstrated to yield strongly similar results, providing additional confidence to the KAON 721 approach that had already been anchored through years of Palomar Observatory experience and the detailed Keck comparisons in KAON 461.

5.8 Configuration Control

KAON 721 is an NGAO configuration controlled document, meaning that revisions to the wavefront error budget spreadsheet is subject to the change control procedures described in KAON 638, "Requirements Approval and Change Process." R. Dekany maintains KAON 721, which includes a worksheet (named "WFE Tool To-Do List") that tracks known issues with calculations or assumptions in the tool, as well as version history and a summary of corrective actions.

The NGAO system architecture choices are documented in the configuration region of the Input Summary tab of the Wavefront Error Budget Tool, KAON 721. Not shown here, but critical to budget fidelity, is an area of the Input Summary that selects optical pass-bands for each WFS camera. (Also not shown are optical transmission models that track expected photon transmission through each AO system configuration.)

6 Detailed Error Budget for Galaxy Assembly Key Science Case

To further illuminate the structure and usage of KAON 721 in evaluating NGAO performance prediction and requirements flowdown, we will now consider the key elements of the tool as generated for one of our key science cases, Galaxy Assembly. The observing scenario information for Galaxy Assembly is included in Table 4.

6.1 Science Path Wavefront Error Budget

The science path wavefront error budget from the 'Optim' sheet of KAON 721 is shown in Table 6. This table is organized (from top-to-bottom) into:

- A heading section, including the AO system configuration and science case name
- An upper high-order wavefront error section
    - Including several key parameters relevant to the underlying calculations in a 'Parameter" column
    - This section is further subdivided loosely into 'fundamental', 'implementation', and 'anisoplanatism' error subsections.
    - Light-blue highlighting in the table generally represents error allocations, e.g. quantities not derived from underlying physical calculations. These are typically further flowed down to subsystem functional requirements in KAON 723.
- A tip-tilt error section
    - Wherein errors are natively calculated in units of residual tip-tilt in milliarcseconds, then converted (via the tip-tilt Strehl ratio and thereafter the primary observing passband wavelength) into equivalent RMS wavefront error estimates, to facilitate the calculation of an 'effective RMS wavefront error' which correctly predicts Strehl performance from the combination of high-order and residual tip-tilt errors
- Strehl predictions
    - Presented as a function of different observing bands, defined in the top-right of the table
- Ensquared and encircled energy predictions
    - For the primary observing band defined by science case, for a range of different spaxel dimensions (e.g. "Spaxel / Aperture Diameter")
    - A choice of encircled or ensquared energy is provided in a (yellow, input) cell
- FWHM predictions
- Sky coverage validation

    - Showing the sky coverage corresponding to the tip-tilt NGS star of the brightness and off-axis distance indicated in the heading section, which is optimized to equal the sky coverage fraction required for each science case (Table 1).
- And finally a section summarizing many of the key system parameters (not previously cited in the HO and TT error sections).
    - These include atmospheric parameter, number of TT WFS, the optimized WFS frame rates, detector read noises, etc.

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	57	PDE/subap/exp
Optim HO integration time:	0.00050	0.0011	sec	948	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	19.0	mV	14.11	mKs
TT integration time	0.00050	0.0047	sec	213	Hz
TT guide star distance	0.0	42.0	arcsec		
TWFS guide star birghtness	LGS	19.0	mV		
TWFS integration time	0.0	2.6688	sec	0.37	Hz
TWFS guide star search radius	0.0	42.0	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimization Controls (be careful & understand how these interact with Solver before use)				
Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Galaxy Assembly**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error		50 nm	60	Subaps
Bandwidth Error		61 nm	**47**	Hz (-3db)
High-order Measurement Error		66 nm	50	W
LGS Tomography Error		37 nm	4	sci beacon(s)
Asterism Deformation Error		16 nm	0.50	m LLT
Chromatic Error		1 nm		Upper limit
Dispersion Displacement Error		1 nm		Estimate
Multispectral Error		25 nm	30	zen; sci wav
Scintillation Error	*K*	12 nm	0.34	Scint index at 0.5um
WFS Scintillation Error		10 nm		Allocation
	115 nm			
Uncorrectable Static Telescope Aberrations		43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations		37 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm		Allocation
Dynamic WFS Zero-point Calibration Error		25 nm		Allocation
Leaky Integrator Zero-point Calibration Error		10 nm		Allocation
Stale Reconstructor Error		15 nm		Allocation
Go-to Control Errors		30 nm		Allocation
Residual Na Layer Focus Change		41 nm	30	m/s Na layer vel
DM Finite Stroke Errors		6 nm	5.3	um P-P stroke
DM Hysteresis		13 nm		from TMT model
High-Order Aliasing Error		17 nm	60	Subaps
DM Drive Digitization		1 nm	16	bits
Uncorrectable AO System Aberrations		33 nm		Allocation
Uncorrectable Instrument Aberrations		30 nm		DAVINCI
DM-to-lenslet Misregistration		15 nm		Allocation
DM-to-lenslet Pupil Scale Error		15 nm		Allocation
	101 nm			
Angular Anisoplanatism Error		16 nm	1.0	arcsec
HO Wavefront Error Margin		45 nm		Allocation

				u'	g'	r'	i'	Z	Y	J	H	K
Total High Order Wavefront Error	153 nm	**160 nm**	**High Order Strehl**	0.00	0.01	0.07	0.17	0.28	0.40	0.53	0.69	0.82

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		1.94 mas	33 nm	**19.0**	mag (mV)
Tilt Bandwidth Error (one-axis)		1.28 mas	22 nm	**9.6**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		3.23 mas	55 nm	**42.0**	arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20	x reduction
Residual Atmospheric Dispersion	*K*	0.12 mas	2 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		1.60 mas	27 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		1.21 mas	21 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	195 nm		Allocation

				u'	g'	r'	i'	Z	Y	J	H	K
Total Tip/Tilt Error (one-axis)	**4.9 mas**	91 nm	**Tip/Tilt Strehl**	0.27	0.39	0.53	0.62	0.70	0.76	0.82	0.89	0.94
Total Effective Wavefront Error		**182 nm**	**Total Strehl (%)**	0.00	0.00	0.04	0.11	0.20	0.30	0.44	0.61	0.76
			FWHM (mas)	8.3	10.1	12.6	14.9	17.3	20.0	24.1	31.2	41.7

		Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		40
Ensquared Energy	*K*	Square	0.09	0.36	0.56	0.75	0.81	0.83	0.85	0.88	0.92		0.50
		Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.20	0.45	0.90		

Sky Coverage — Galactic Latitude 60 deg

Corresponding Sky Coverage **30%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2

AO Modes of Operation	
Science AO Mode:	MOAO
LOWFS AO Mode:	Indep PnS

Number of WFS's for TT measurement	
TT	2
TTFA	1
3x3	0
HOWFS	0

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	

Observation Parameters		
Max Exposure Time	1800	sec

LO WFS Magnitudes								
20.0	19.3	18.4	17.5	17.2	16.8	16.3	15.2	14.1

Derived Values		
HO WFS Rate	948	Hz
Detected PDE/subap/exp	57	
LO WFS Rate	213	Hz
Detected PDE/subap/exp	150	

Table 6. Galaxy Assembly Case Wavefront and Ensquared Energy Budget

6.2 TT Sharpening Budget

KAON 721 includes an entirely separate wavefront error budget to describe the sharpening of TT NGS, which is a key input to understand the science path performance budget described in §6.1. An example of this for the Galaxy Assembly case is presented in Table 7.32

Keck LOWFS Wavefront Error Budget Summary — Version 2.1

Mode:	**NGAO LGS**
Instrument:	**DAVINCI**
Sci. Observation:	**Galaxy Assembly**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μm)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μm)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/D (mas)	7	10	13	15	18	21	26	34	46

LOWFS High-order Errors (Mode) 42.4 arcsec off-axis			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			90 nm	30	Acts Across
Bandwidth Error			57 nm	54	Hz (-3db)
High-order Measurement Error			79 nm	8.33	W
LGS Tomography Error			150 nm		SCAO
Asterism Deformation Error			16 nm	0.50	m LLT
Chromatic Error			1 nm		Upper limit
Dispersion Displacement Error			2 nm		Estimate for IR TT
Multispectral Error			25 nm	30	zen; flux-wght wav
Scintillation Error	H		20 nm	0.34	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		203 nm			
Uncorrectable Static Telescope Aberrations			60 nm	30	Acts Across
Uncorrectable Dynamic Telescope Aberrations			32 nm		
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			30 nm		Allocation
Residual Na Layer Focus Change			42 nm	30	m/s Na layer vel
DM Finite Stroke Errors			15 nm	1.5	um P-P MEMS strok
DM Hysteresis			2 nm	from LAO	
High-Order Aliasing Error			17 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			62 nm		Allocation
Uncorrectable Instrument Aberrations			30 nm	DAVINCI	Indep PnS
DM-to-lenslet Misregistration			25 nm		Allocation
DM-to-lenslet Pupil Scale Error			25 nm		Allocation
		124 nm			
Angular Anisoplanatism Error			0 nm	41.42	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		238 nm	**238 nm**		

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.00	0.02	0.05	0.12	0.23	0.42	0.62

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundanc	3	x 10^9 cm^{-2}

AO Modes of Operation	
Science AO Mode	MOAO
LOWFS AO Mode	Indep PnS

System Parameters			
Effective PnS GS radius	0.34	arcmin	
PnS LGS Power	8.33	W	
BTO Transmission	0.60		
PnS HO WFS Transmission	0.38		
PnS WFS Type	SH	using	CCID74
PnS WFS Noise	1.7	e- rms	
PnS HO WFS Anti-aliasing	NO		
Max TT Rejection Bandwidth	100	Hz	

Derived Values		
PnS HO WFS Rate	1079	Hz
Detected PDE/subap/exp	127	
LGS return per beacon	290	ph/cm^{-2}/sec

Observation Parameters		
Max Exposure Time	1800	sec

Table 7. Galaxy Assembly TT Sharpening Budget

The TT sharpening budget includes many of the same error terms as the science path error budget with several notable exceptions:

- As it represents the 'short exposure' wavefront error of the TT NGS, there are no tip-tilt error terms included here
- Focal anisoplanatism error in the NGAO case is calculated using a separate, single LGS beacon
  - o The NGAO RTC architecture only supports independent patrolling LGS sharpening based on this one beacon; no advantage of fixed asterism tomography is assumed or allowed.
- The 'Science band' wavelength definitions in this table represent the sharpening of the TT NGS in different bands. The actual photometry of the sharpened TT star is based upon the selection of LO WFS pass-bands in the 'Input Summary' sheet.

The output of the TT sharpening budget becomes part of the science path residual tip-tilt error estimate (§6.1), as we take into account the near-IR Strehl ratio of the tip-tilt NGS when calculating the tip-tilt measurement error. The NGAO architectural choice of independently sharpening the tip-tilt NGS using the patrolling WFS / LO WFS DM subsystem significantly reduces the dependency of NGAO performance on the particular vertical distribution of turbulence from night-to-night, though performance will vary as a function of overall seeing.

6.3 TWFS Budget

During PD phase, NGAO TWFS budget development was begun, but not taken to its full implementation. Currently, KAON 721 estimates the focus term error that results from the SNR and bandwidth (incl. atmospheric averaging) behavior of the (typically) off-axis visible TWFS star. The initial implementation is summarized in Table 8

Truth Wavefront Sensor High-order Errors	Wavefront Error (rms)	Wavefront Error Focus Only(rms)	Parameter
TWFS Measurement Error	94 nm	19 nm	19.0 Mv
Residual Na Layer Focus Change		30 nm	
Time averaged total anisoplanatism Error	190 nm		2.1 Integration time (secs)
Time averaged focus anisoplanatism Error		23 nm	
Total High Order Wavefront Error	**212 nm**		
Residual Na Layer Focus Change		**42 nm**	
Sky Coverage Galactic Lat. 60 deg			
Corresponding Sky Coverage	**30%**		

Table 8. Galaxy Assembly TWFS Budget

The TWFS budget is used in the science path error budget (§6.1) to determine the final error due to vertical motion and redistribution of the mesospheric sodium layer. During the DD phase, we intend to further expand the fidelity and detail of the TWFS error budget to include additional low-order modes.

7 Galaxy Assembly Case Performance Sensitivities

7.1 LGS Performance vs. Seeing

NGAO will have to operate in a wide range of natural seeing conditions, so it is interesting to understand the sensitivity of performance to changes in the Fried parameter, r_0. This is shown for the Galaxy Assembly Science Case in Figure 2.

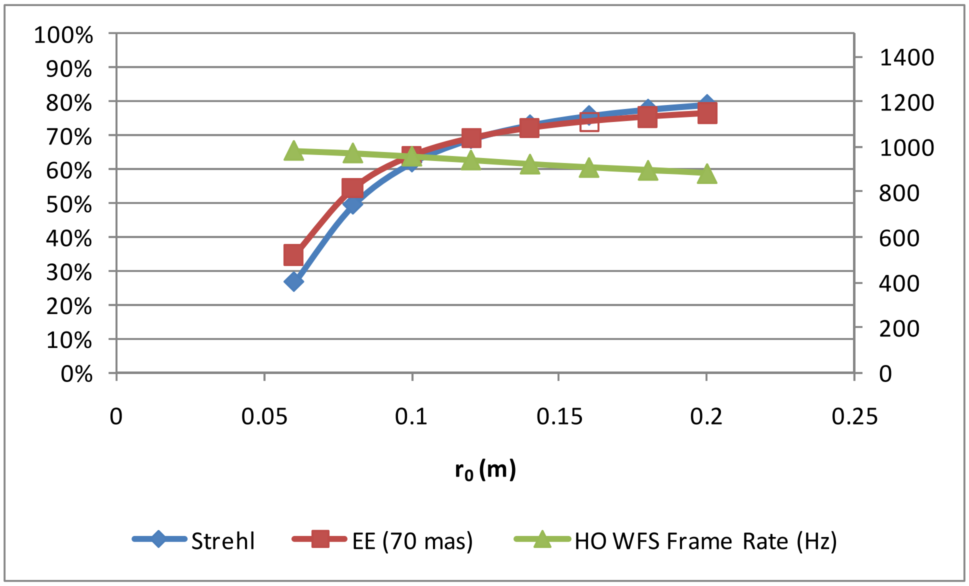

Figure 2. K-band performance for the Galaxy Assembly Science Case as a function of r_0 at 0.5 microns.

7.2 LGS Performance vs. Wind Speed

The 3-dimensional wind profile of the atmosphere above Mauna Kea can vary dramatically. Although our median a value for turbulence-weighted wind speed is 9.5 m/s (Appendix B), we would like to understand how performance degrades with increasing wind speed, and how it might improve under calmer conditions. Figure 3 demonstrates the sensitivity of performance, which is rather benign for the Galaxy Assembly Science Case, even for wind speeds treble our median assumption. As the wind speed is increased, the corresponding HO WFS frame rate increases (and recall, in the current KAON 721 model, this also simultaneously increases the HO WFS CCD pixel readout rate.) For a fixed pixel read rate, NGAO will have somewhat more performance sensitivity to high wind speeds, as the rejection bandwidth of atmospheric turbulence may not be able to keep up so optimally with increasing frame rate.

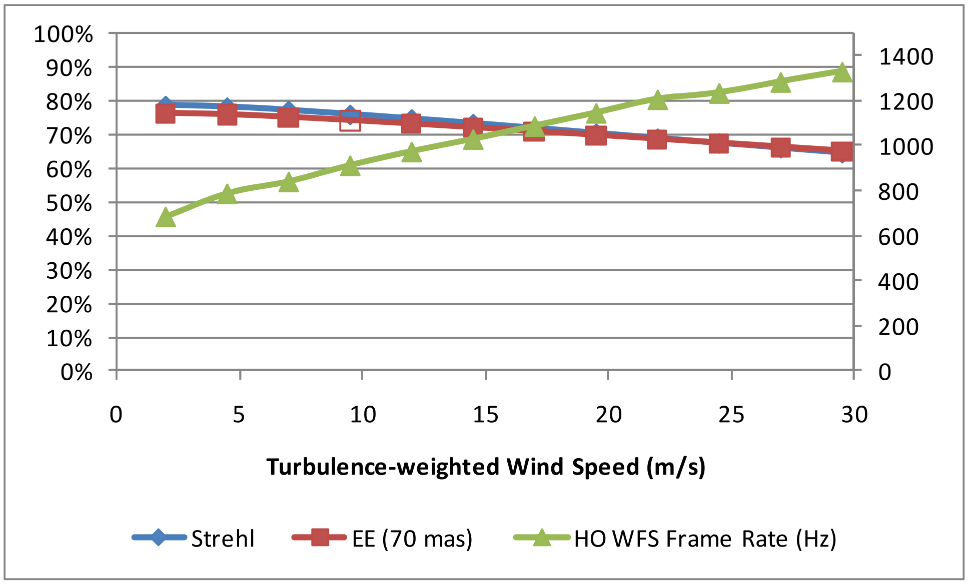

Figure 3. K-band performance for the Galaxy Assembly Science Case as a function of turbulence-weighted wind speed. The open marker indicates the median 9.5 m/s wind speed condition.

7.3 LGS Performance vs. Laser Return

Experience with the first-generation sodium D2-line resonant excitation LGS at Lick, Keck, and Palomar Observatories has shown that measured sodium photoflux can vary widely due to be sodium abundance fluctuations (see §7.10), but also because of variability in laser power and degradations in optical transmission in beam transfer uplink or AO system downlink optical systems.

We are interested in understanding the sensitivity of NGAO to variations in the expected sodium return photoflux. The results of two trade studies are shown in Figure 4 and Figure 5. In the first of these, we consider the impact of different levels of laser (spigot) power in absolute terms (assuming our usual "SOR-like" laser return) while in the second, we describe it as a percentage of the expected laser return (typically 55 photodetection events (PDE) / exposure time / subaperture, or 57 / 0.0011 / (.1825^2) = 1.55×10^6 PDE/sec/m^2 or ~155 PDE/sec/cm^2, for each of the 12.5W (spigot) fixed asterism LGS[19]).

[19] We assume 75 ph/sec/cm^2/W return from a 3×10^9 atoms/cm^2 sodium layer (itself from Denman's reported 150 ph/sec/cm^2 from Albuquerque with 4×10^9 atoms/cm^2 – see KAON 721), with 50W/4*.6 (BTO)*.88 (Atm) = 6.6 W per beacon delivered to mesosphere (495 ph/sec/cm^2 at mesosphere), followed by T=0.35, QE=0.85 on the downlink results in about 155 ph/sec/cm^2 detected by the WFS.

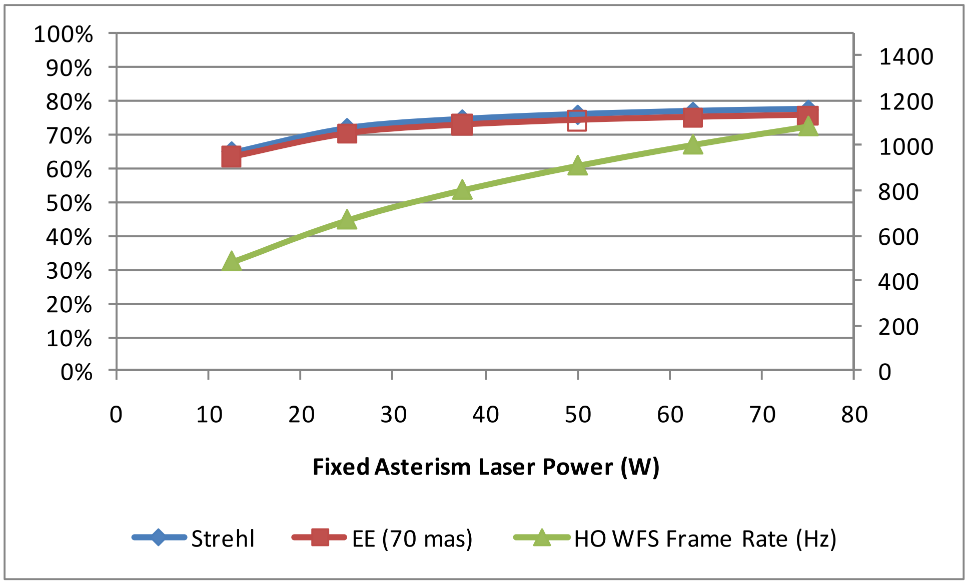

Figure 4 K-band wavefront error performance for the Galaxy Assembly Science Case as a function of fixed asterism laser power, holding patrolling asterism laser power constant at 25W (e.g. 3 x 8.33 W each.) The open marker indicates the baseline 50W of fixed asterism laser power (spigot).

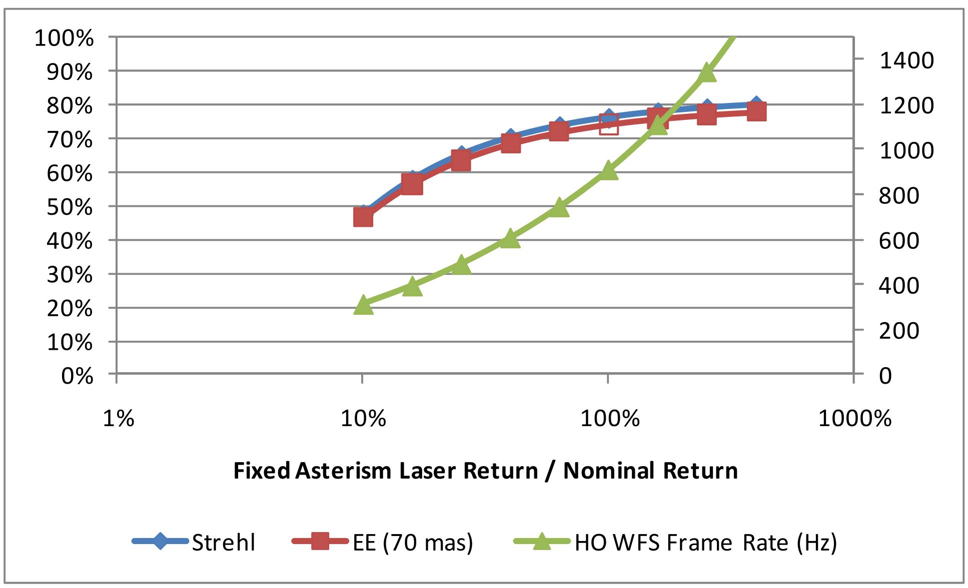

Figure 5. K-band wavefront error performance for the Galaxy Assembly Science Case as a function of fixed asterism laser return, relative to the expected return using our baseline conditions model (e.g. 3 x 10^9 atoms/cm^2 sodium density, SOR-laser-like return, delivered and return transmission assumptions, etc.), holding patrolling asterism laser power constant at 25W (e.g. 3 x 8.33 W each.) The robustness of NGAO to less-than-expected laser return is clear for this science case.

7.4 LGS Performance vs. Sky Fraction

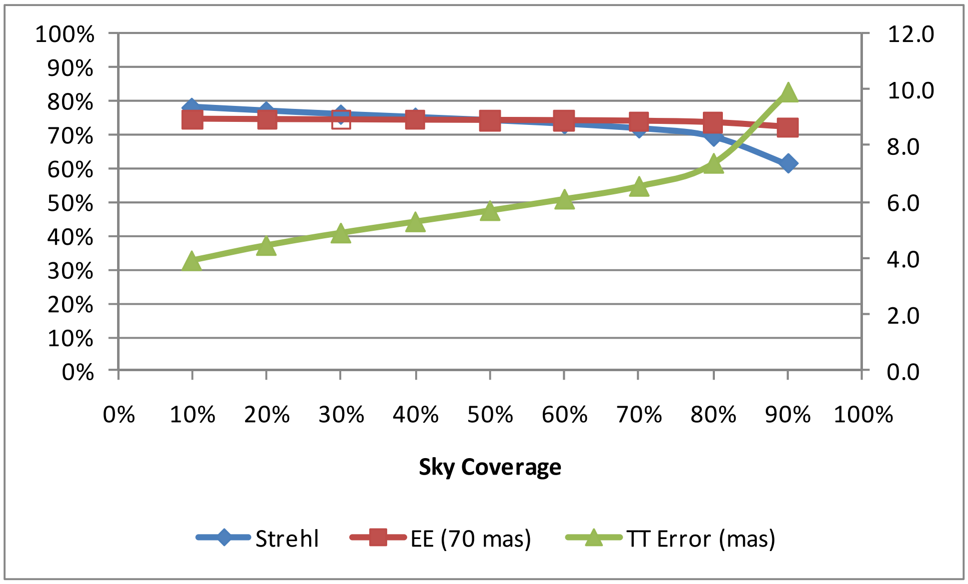

Figure 6. K-band wavefront error performance for the Galaxy Assembly Science Case as a function of sky coverage percentage, representing the likelihood of finding three NGS of sufficient brightness to achieve the indicated performance, within the FoR of the LO WFS. The residual TT error varies from about 4 mas to about 9 mas as the sky coverage fraction is increased.

7.5 LGS Performance vs. LO WFS Passband

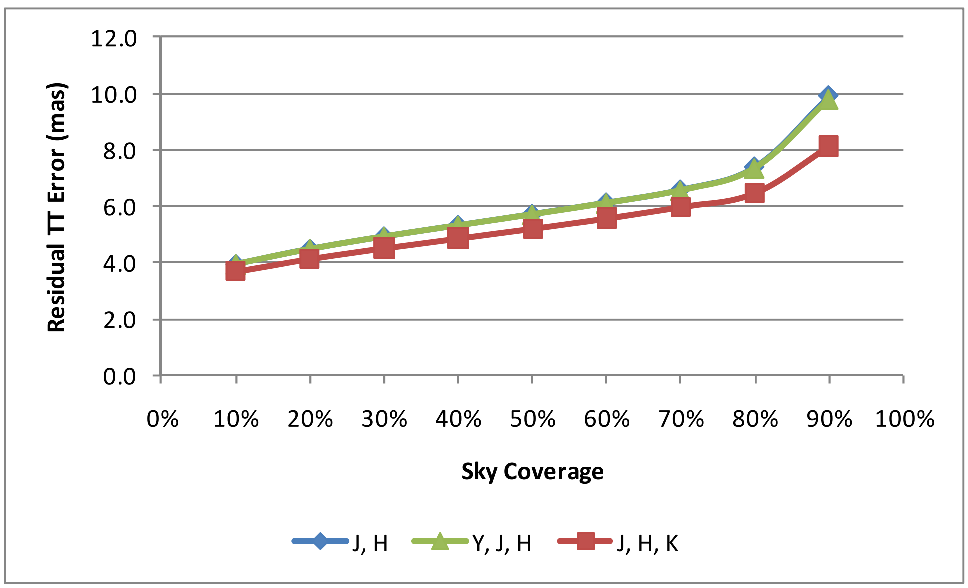

Figure 7. Residual TT error for the Galaxy Assembly Science Case as a function of sky coverage percentage, for three different choices of LO WFS passband. Inclusion of the design-complicating K-band is comparable to the uncertainty in our models, excepting perhaps at the highest sky fraction, where the advantage of including K-band would probably be real. Note, KAON 721 does not currently account for inter-filter-band sky emissions. Thus, these results should be considered for e.g. J + H, not the full range J through H. As such, the relative advantage of including K-band is probably overstated here.

Based on this marginal performance benefit of including K-band in the LO WFS passband shown in Figure 7, we have made the design decision to design for J+H alone, simplifying the LO WFS design, which would otherwise demand a cryogenic Lyot stop within each of the LO WFS cryostats.

7.6 LGS Performance vs. Spaxel Size

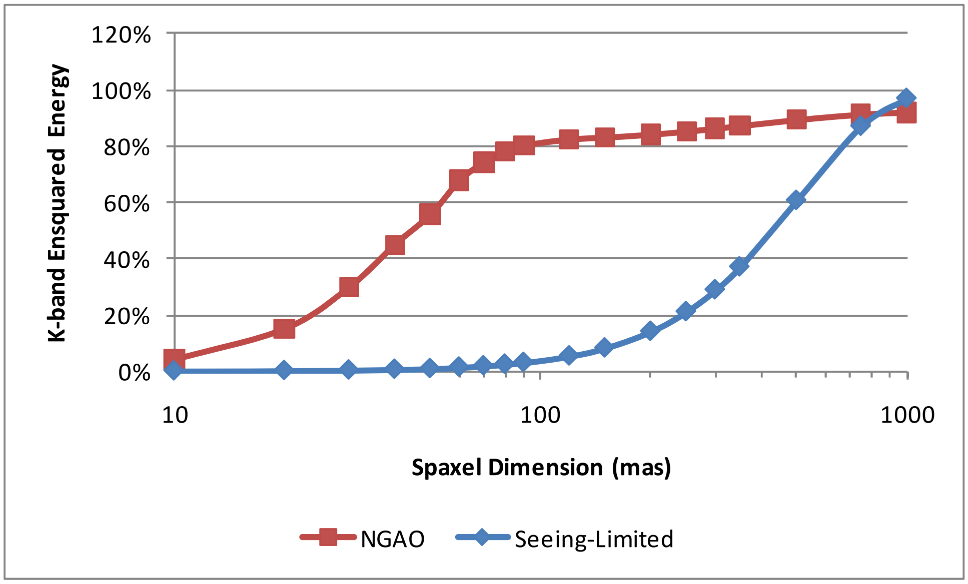

Figure 8. K-band Ensquared Energy vs. Spaxel Size for the Galaxy Assembly Science Case for NGAO correction and, for comparison, a seeing-limited PSF in median seeing conditions. (The relative transmission loss of NGAO compared to a Nasmyth-mounted seeing-limited instrument is not represented here – these curves reflect PSF shape only.)

7.7 LGS Performance vs. Number of LO WFS NGS

[XXX work to do – perform this trade study (will need to estimate the blind mode suppression from 1 or 2 NGS, not sure this is covered in KAON 429.]

7.8 NGS Performance vs. Natural Guide Star Brightness\

[XXX work to do – this should be straightforward for NGS science mode]

7.9 Interferometer Performance vs. Natural Guide Star Brightness

[XXX work to do – Do we need to define an interferometer science case to understand this? If this is simply bright NGS mode performance, does it differ from the previous section? If this is a LGS case, then we presumably want to vary a bright on-axis TT star? – Claire, Peter, can you help define this?]

7.10 Monte Carlo Error Budget Modeling Results

Although practically useful in understanding the sensitivities of NGAO performance to both seeing and turbulence-weighted wind speed variations, in practice NGAO will see on any given night seeing and wind speed values that are random variables drawn from some statistical distributions. In fact, there exists considerable detail on the statistics of these parameters at Mauna Kea. For our current purpose, however, an approximate form of these distributions will suffice to indicate the typical distribution of performance we might expect from a large number of observing nights. To quickly model this, we assume that both r_0 and wind speed are drawn from Gaussian probability distributions. Following the technique in 'Numerical Recipes in C, 2nd Ed', page 289, we generated in Excel draws of the form:

	Mean	Standard Deviation, σ
r_0 at 0.5 microns	0.16 m	0.025 m
Wind speed	9.5 m/s	4 m/s

where the distribution standard deviations, σ, are coarse estimates based on KAON 303. (A detailed determination of σ Is unlikely to improve these results, as I contend we are within the uncertainty level of the model[20].)

The results of 252 random draws (and frame rate optimizations) from this joint probably distribution is shown in Figure 9, for the case of mesospheric sodium abundance held constant at the below-median level of 3 x 10^9 atoms/cm^2. Note, unlike the current Keck 2 AO system, NGAO is seen to very rarely deliver performance less than about 60% K-band Strehl ratio. Moreover, NGAO is expected to deliver K-Strehls within a few percent of 78%, across varying different atmospheric conditions. This is a rather remarkable qualitative difference over current AO, one that we expect will dramatically improve both photometric accuracy and astrometric precision.

[20] For these Gaussian distributions, we also truncate the distribution to avoid negative values. Although not strictly valid, in practice it has little effect on the results shown here (e.g. we're not primarily interested in these rare outlier events.)

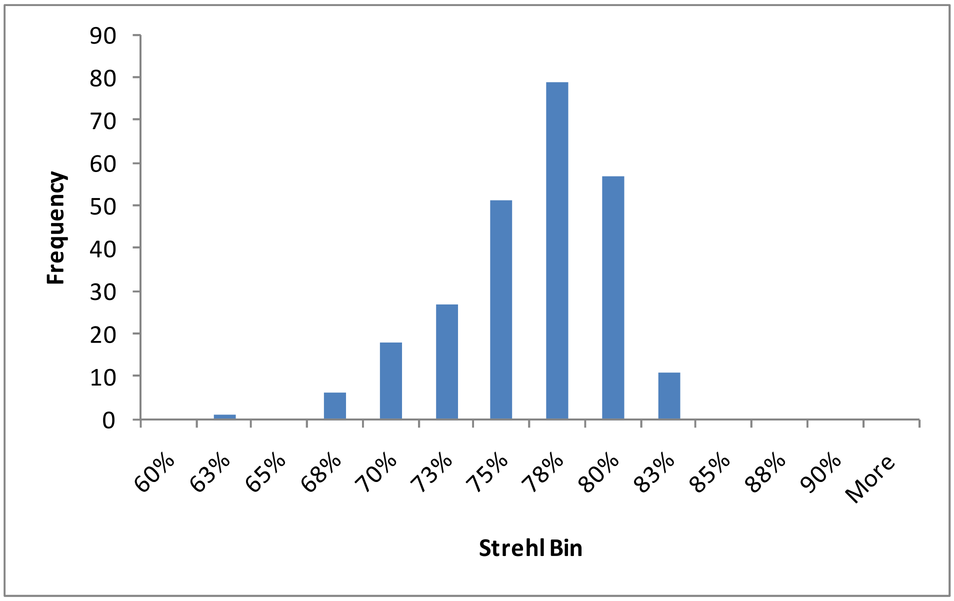

Figure 9. Predicted K-band performance distribution for NGAO based upon 252 r_0 and wind speed draws, holding sodium abundance constant at 3e9 atoms/cm^{2}', for the Galaxy Assembly Science Case.

Because sodium abundance can also vary, we repeated this random draw experiment, adding it as a third joint random variable:

	Mean	Standard Deviation, σ
Sodium abundance	3.6 x 10^9 atoms/cm^2	1.0 x 10^9 atoms/cm^2

where the mean is taken from KAON 416. We have estimated the standard deviation from Keck LGS experience which has shown that the large majority (~90%) of time density is estimated to be between 1.6 x 10^9 and 5.6 x 10^9 atoms/cm^2 (e.g. +- 2σ). This result, for 394 random draws, is shown in Figure 10. Not surprisingly, this histogram is shifted to somewhat higher performance compared to our earlier sub-median sodium abundance curve. Because sometimes the abundance can fall, even in conjunction with good seeing and slow winds, the (relatively) poorer performance tail is now seen to be extended, though still almost always above 60% K-Strehl.

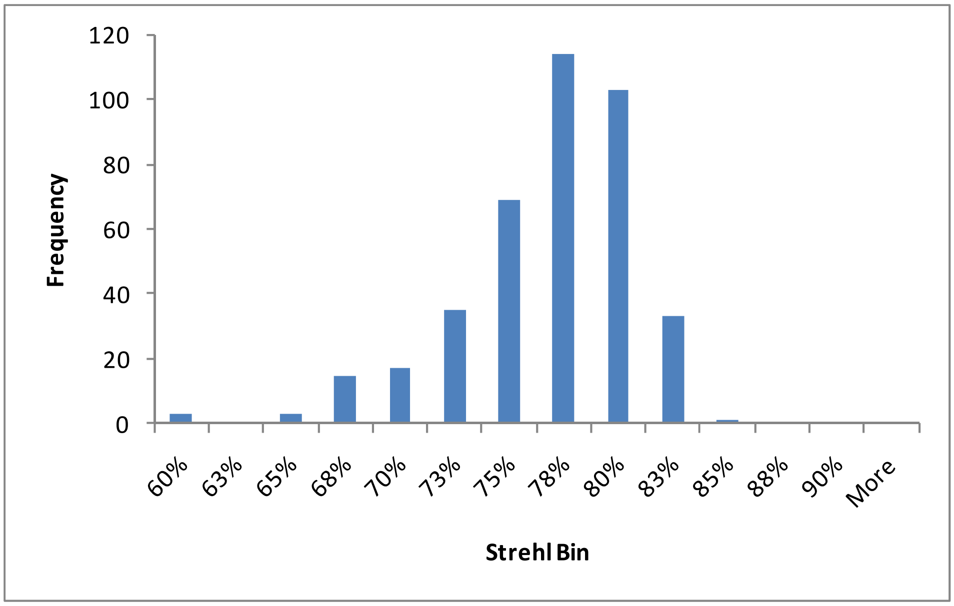

Figure 10. Predicted K-band performance distribution for NGAO based upon 394 r_0, wind speed, and sodium abundance draws for the Galaxy Assembly Science Case.

To better appreciate the advantage of NGAO over current Keck 2 AO, we repeated the experiment described in Figure 10 with a mirror experiment, using the same parameter distributions, for our model of the Keck 2 AO system (previously validated as described in KAON 461). This result is shown in Figure 11. The first obvious benefit of NGAO is an approximately 3x improvement in K-band Strehl ratio over current Keck 2 AO, which direct improves telescope sensitivity for background-limited imaging. The difference in results distribution width is also quite striking, particularly if one considers the *relative* stability of the predicted results, with NGAO showing perhaps +- 4% variation around a 78% peak (+- 5% relative), while the Keck 2 AO result shows +- 10% around a 30% median, which is more like +- 33% relative variation.

The skewness of these distributions is also worth noting. For Keck 2 AO, the longer tail is toward good performance, so it is more likely that an observer will have heard of someone at some time having a particularly good result with Keck 2 AO, but the median performance, they're average experience with AO, tends to fall short of this. For NGAO, on the other hand, we expect the user experience to be more often consistent with the maximum capability of the system. The occasional unfortunate night for an NGAO observer will doubtless draw heartfelt condolences from their colleagues.

More practically, NGAO instrument development will also benefit from this tendency to deliver more predictable image quality, perhaps by reducing the number of configurations, such as plate scales, that is typically necessary when delivered performance is widely variable.

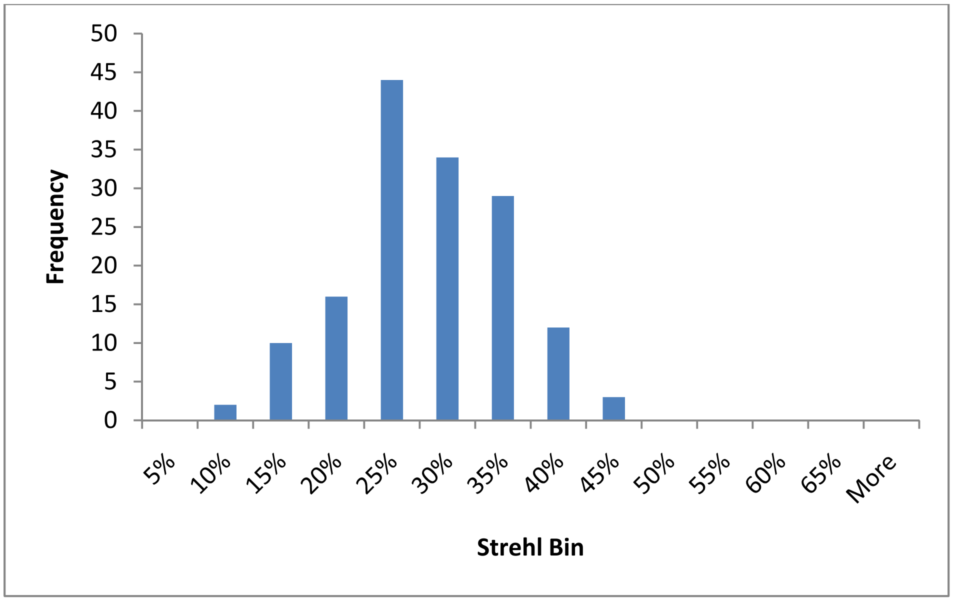

Figure 11 Predicted K-band performance distribution for the current Keck 2 AO system based upon 150 r_0, wind speed, and sodium abundance draws for the Galaxy Assembly Science Case. Note the change in Strehl Bin scale compared to the NGAO predictions.

7.11 LAOS Simulation Modeling Results

[XXX – this section is unlikely to survive; we haven't done these sims and it's unclear if we will have the time – Chris, want to comment?]

8 NGAO Science Cases Performance Summaries

KAON 721 captures the observing scenario information relevant to each of the NGAO science cases. Evaluation of the NGAO performance for each case has been automated using VBA for Applications scripts that:

- For each LGS and NGS observing scenario
  - Optimize HO WFS frame rate, TT WFS frame rate, off-axis NGS LO WFS frame rate, and TWFS frame rate; consistent with the requirements for sky coverage fraction (all as appropriate to that configuration).
  - Capture the summary error budget as shown on the 'Optim' worksheet into a new "Output" file independent of KAON 721 (copy by value, essentially).

8.1 Performance Summary

The performance summary of the NGAO PD phase design for all these Science Cases is summarized in Table 9.

KAON 721 Case	Science Case	High-order RMS Wavefront Error (nm)	RMS TT Error (mas)	Effective Total RMS Wavefront Error (nm)	Ensquared Energy within a 70 mas spaxel	Observing Passband
1	Galaxy Assembly	160	4.9	182	75%	K
2	Nearby AGN	161	4.8	179	29%	Z
3	Galactic Center	186	2.2	190	60%	H
4	Galactic Center Spectra	189	2.4	194	59%	H
5	Exo-planets	158	7.8	207	69%	H
6	Minor Planets	159	5.0	179	30%	Z
7	Io	116	2.1	119	54%	Z
8	QSO Host Galaxies	154	2.3	157	71%	H
9	Gravitational Lensing	171	5.0	192	65%	H
10	Astrometry Science	171	4.7	189	65%	H
11	Transients	156	2.6	162	31%	Z
12	Resolved Stellar Populations	215	6.4	236	6%	I'
13	Debris Disks and YSOs	157	3.1	165	19%	I'
14	Gas Giant Planets	169	3.5	180	73%	K
15	Ice Giant Planets	190	4.4	204	59%	H

Table 9. Summary of predicted wavefront error performance for all NGAO science cases.

[XXX – work to do: need more interpretation of these results. Is this good or bad? Will NGAO meet the science objectives we set out?]

8.2 Science Path WFE using NGS WFS in TWFS mode

There are three NGAO modes of operation that require use of the visible-light NGS WFS in a 5x5 subaperture pupil sampling mode:

- Pupil Fixed mode operation (typical of exoplanet searches and characterization),
- Image Fixed mode when the availability of field NGS for LO WFS sensing of TT and blind mode sensing is not favorable compared to use of the science target itself for both TT and blind mode information, and
- Interferometer mode which needs to use NGS WFS for both TT and TWFS functionality. In this mode, NGAO would often use an NGS other than the on-axis science object.

In theory, it may be possible to combine information from the NGS WFS in TWFS mode with information from the LO WFS, to further optimize performance, but this will not be investigated here. Instead, we would like to understand the TT performance (only) of the NGS WFS in TWFS mode, as a function of science target brightness, and more specifically we're interested in knowing how the red-wavelength NGS WFS cutoff choice affects performance in the NGS WFS TWFS mode. The results of just such a trade study are shown in Figure 12.

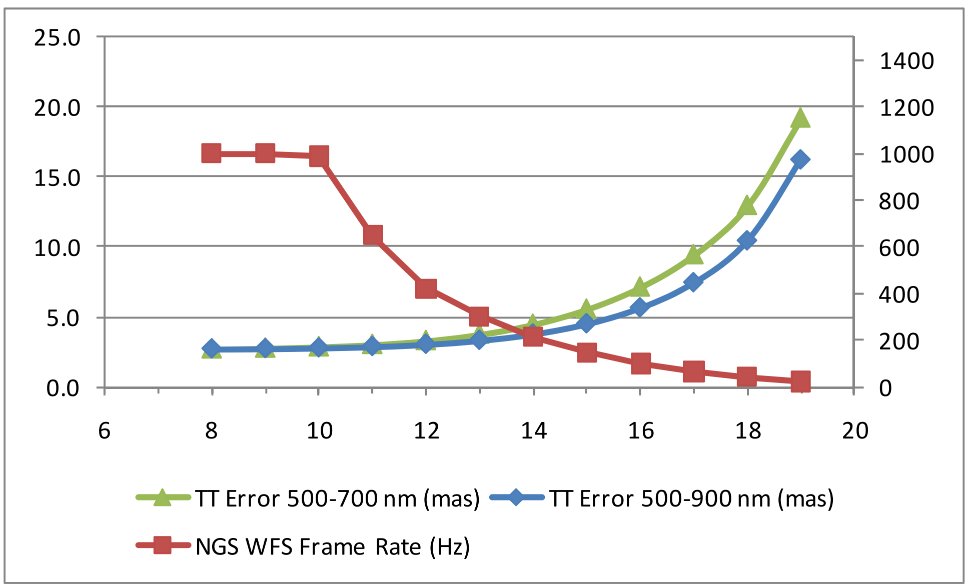

Figure 12. Performance of the NGAO NGS WFS for TT measurement, when operating in 5x5 subaperture TWFS mode, for NGS passband approximately 500 – 900 nm, compared to passband approximately 500 – 700 nm. These curves are optimized for best TT performance, and do not include the degradation of TWFS sensing of the laser tomography blind modes as the NGS WFS frame rate is slowed. The indicated optimal NGS WFS frame rate corresponds to the 500 – 900 nm passband case.

In generating Figure 12, we assume that the NGS WFS frame rate is optimized to provide the best TT measurement, without regard to the potential impact on its ability to accurately measure the laser tomography blind modes. If we assume that the need for accurate blind mode measurement requires us to operate the NGS WFS in TWFS mode no slower than 200 Hz (an admittedly arbitrary number), the quality of NGS WFS TT sensing breaks down considerable faster, as shown in Figure 13.

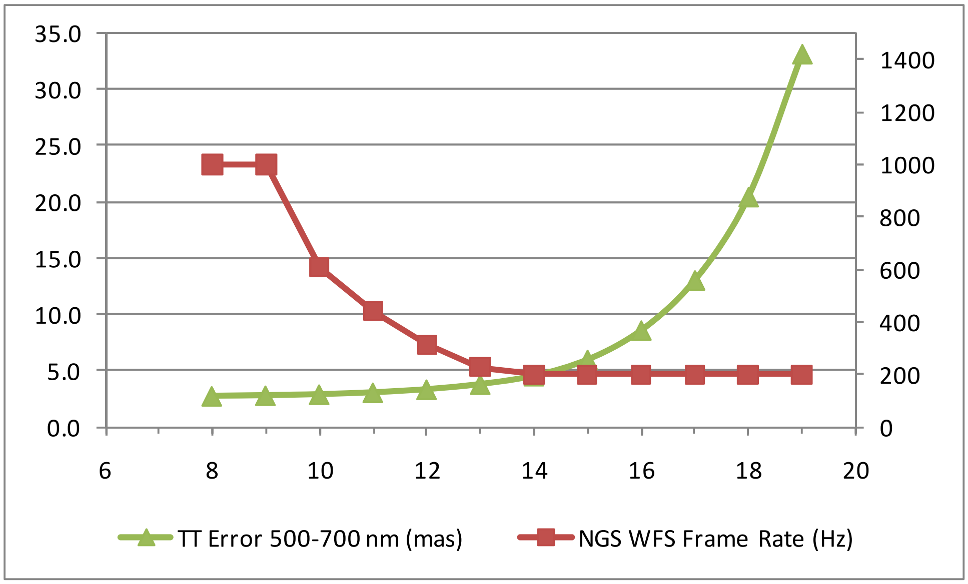

Figure 13 Performance of the NGAO NGS WFS for TT measurement, when operating in 5x5 subaperture TWFS mode, for NGS passband approximately 500 – 700 nm, with a minimum frame rate limit of 200 Hz. This may be more indicative of TT operation when the NGS WFS is required to read out relatively fast to maintain good blind mode measurement.

Appendix A: Key Science Case Detailed Error Budgets

Galaxy Assembly

Optimizations/sky coverage calculations				COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings		Optimize			
HO guide star brightness	LGS		mV	57	PDE/subap/exp	Optimize LGS Off-Pointing?	N		
Optim HO integration time:	0.00050	0.0011	sec	948	Hz	Optimize LGS Range Gate?	N		
Optim subaperture width:	0.174	0.174	meters	60	Subaps	Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
TT guide star brightness	LGS	19.0	mV	14.11	mKs				
TT integration time	0.00050	0.0047	sec	213	Hz				
TT guide star distance	0.0	42.0	arcsec						
TWFS guide star birghtness	LGS	19.0	mV						
TWFS integration time	0.0	2.6688	sec	0.37	Hz				
TWFS guide star search radius	0.0	42.0	arcsec						
Number of laser beacons		4.0							
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS		Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Galaxy Assembly**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter		Strehl Ratio (%)								
Atmospheric Fitting Error			50 nm	60	Subaps									
Bandwidth Error			61 nm	**47**	Hz (-3db)									
High-order Measurement Error			66 nm	50	W									
LGS Tomography Error			37 nm	4	sci beacon(s)									
Asterism Deformation Error			16 nm	0.50	m LLT									
Chromatic Error			1 nm		Upper limit									
Dispersion Displacement Error			1 nm		Estimate									
Multispectral Error			25 nm	30	zen; sci wav									
Scintillation Error	*K*		12 nm	0.34	Scint index at 0.5um									
WFS Scintillation Error			10 nm		Allocation									
		115 nm												
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil									
Uncorrectable Dynamic Telescope Aberrations			37 nm		Dekens Ph.D									
Static WFS Zero-point Calibration Error			25 nm		Allocation									
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation									
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation									
Stale Reconstructor Error			15 nm		Allocation									
Go-to Control Errors			30 nm		Allocation									
Residual Na Layer Focus Change			41 nm	30	m/s Na layer vel									
DM Finite Stroke Errors			6 nm	5.3	um P-P stroke									
DM Hysteresis			13 nm		from TMT model									
High-Order Aliasing Error			17 nm	60	Subaps									
DM Drive Digitization			1 nm	16	bits									
Uncorrectable AO System Aberrations			33 nm		Allocation									
Uncorrectable Instrument Aberrations			30 nm		DAVINCI									
DM-to-lenslet Misregistration			15 nm		Allocation									
DM-to-lenslet Pupil Scale Error			15 nm		Allocation									
		101 nm												
Angular Anisoplanatism Error			16 nm	1.0	arcsec									
HO Wavefront Error Margin			45 nm		Allocation									
Total High Order Wavefront Error		153 nm	**160 nm**	**High Order Strehl**		0.00	0.01	0.07	0.17	0.28	0.40	0.53	0.69	0.82

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter		Strehl ratios (%)								
Tilt Measurement Error (one-axis)		1.94 mas	33 nm	**19.0**	mag (mV)									
Tilt Bandwidth Error (one-axis)		1.28 mas	22 nm	**9.6**	Hz (-3db)									
Tilt Anisoplanatism Error (one-axis)		3.23 mas	55 nm	**42.0**	arcsec from sci									
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20	x reduction									
Residual Atmospheric Dispersion	*K*	0.12 mas	2 nm	20	x reduction									
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height									
Non-Common-Path Tip-Tilt Errors		1.60 mas	27 nm	3.2 mas/l	Allocation									
Residual Telescope Pointing Jitter (one-axis)		1.21 mas	21 nm	29	Hz input disturbance									
TT Error Margin		2.00 mas	195 nm		Allocation									
Total Tip/Tilt Error (one-axis)		**4.9 mas**	91 nm	**Tip/Tilt Strehl**		0.27	0.39	0.53	0.62	0.70	0.76	0.82	0.89	0.94
Total Effective Wavefront Error			**182 nm**	**Total Strehl (%)**		0.00	0.00	0.04	0.11	0.20	0.30	0.44	0.61	0.76
				FWHM (mas)		8.3	10.1	12.6	14.9	17.3	20.0	24.1	31.2	41.7

		Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		40
Ensquared Energy	*K*	Square	0.09	0.36	0.56	0.75	0.81	0.83	0.85	0.88	0.92		0.50
		Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.20	0.45	0.90		

Sky Coverage	Galactic Latitude	60 deg	
Corresponding Sky Coverage		**30%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters			System Parameters				LO WFS Magnitudes		
Zenith Angle	30	deg	LGS Asterism Radius	0.17	arcmin		20.0 19.3 18.4 17.5 17.2 16.8 16.3 15.2 14.1		
r0	0.147	m	LGS Power	50	W				
theta0_eff	2.145	arcsec	BTO Transmission	0.60			Derived Values		
Wind Speed	10.97	m/s	HO WFS Transmission	0.38			HO WFS Rate	948	Hz
Outer Scale	50	m	HO WFS Type	SH	using	CCID74	Detected PDE/subap/exp	57	
Sodium Abundance	3	x 109 cm-2	HO WFS Noise	1.7	e- rms				
			HO WFS Anti-aliasing	NO					
AO Modes of Operation			LO WFS Transmission	0.29			LO WFS Rate	213	Hz
Science AO Mode:	MOAO		LO WFS Type	SH	using	H2RG	Detected PDE/subap/exp	150	
LOWFS AO Mode:	Indep PnS		LO WFS Noise	3.2	e- rms				
			LO WFS Star Type:	M					
Number of WFS's for TT measurement			Max TT Rejection Bandwidth	100	Hz				
TT	2								
TTFA	1		Observation Parameters						
3x3	0		Max Exposure Time	1800	sec				
HOWFS	0								

Nearby AGN

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	57	PDE/subap/exp
Optim HO integration time:	0.00050	0.0011	sec	948	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	19.0	mV	14.12	mKs
TT integration time	0.00050	0.0049	sec	204	Hz
TT guide star distance	0.0	41.8	arcsec		
TWFS guide star birghtness	LGS	19.0	mV		
TWFS integration time	0.0	2.0988	sec	0.48	Hz
TWFS guide star search radius	0.0	41.8	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Nearby AGN**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			50 nm	60	Subaps
Bandwidth Error			61 nm	**47**	Hz (-3db)
High-order Measurement Error			66 nm	50	W
LGS Tomography Error			37 nm	4	sci beacon(s)
Asterism Deformation Error			16 nm	0.50	m LLT
Chromatic Error			3 nm		Upper limit
Dispersion Displacement Error			8 nm		Estimate
Multispectral Error			22 nm	30	zen; sci wav
Scintillation Error	Z		16 nm	0.34	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		115 nm			
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			37 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			30 nm		Allocation
Residual Na Layer Focus Change			42 nm	30	m/s Na layer vel
DM Finite Stroke Errors			6 nm	5.3	um P-P stroke
DM Hysteresis			13 nm		from TMT model
High-Order Aliasing Error			17 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			33 nm		Allocation
Uncorrectable Instrument Aberrations			30 nm		DAVINCI
DM-to-lenslet Misregistration			15 nm		Allocation
DM-to-lenslet Pupil Scale Error			15 nm		Allocation
		102 nm			
Angular Anisoplanatism Error			16 nm	1.0	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		153 nm	**161 nm**	**High Order Strehl**	

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.07	0.17	0.28	0.39	0.53	0.69	0.81

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		1.91 mas	32 nm	**19.0**	mag (mV)
Tilt Bandwidth Error (one-axis)		1.33 mas	23 nm	**9.3**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		3.22 mas	53 nm	**41.8**	arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20	x reduction
Residual Atmospheric Dispersion	Z	0.68 mas	13 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.80 mas	14 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		1.25 mas	21 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	78 nm		Allocation
Total Tip/Tilt Error (one-axis)		**4.8 mas**	82 nm	**Tip/Tilt Strehl**	
Total Effective Wavefront Error			**179 nm**	**Total Strehl (%)**	

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.29	0.41	0.55	0.64	0.71	0.77	0.83	0.89	0.94
Total Strehl (%)	0.00	0.00	0.04	0.11	0.20	0.30	0.44	0.62	0.76
FWHM (mas)	8.2	10.0	12.5	14.9	17.3	20.0	24.0	31.2	41.7

Spaxel / Aperture Diameter (mas)		15	35	50	70	90	120	240	400	800		380
Ensquared Energy Z	Square	0.14	0.27	0.29	0.29	0.30	0.32	0.40	0.51	0.69		0.50
	Seeing-Limited	0.00	0.00	0.01	0.01	0.02	0.04	0.14	0.34	0.81		

Sky Coverage — Galactic Latitude 60 deg

Corresponding Sky Coverage **30%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	900	sec	

LO WFS Magnitudes								
20.0	19.3	18.4	17.5	17.2	16.8	16.3	15.2	14.1

Derived Values		
HO WFS Rate	948	Hz
Detected PDE/subap/exp	57	
LO WFS Rate	204	Hz
Detected PDE/subap/exp	154	

Galactic Center Imaging

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	48	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	1023	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	12.2	mV	4.60	mKs
TT integration time	0.00050	0.0005	sec	2000	Hz
TT guide star distance	0.0	5.6	arcsec		
TWFS guide star birghtness	LGS	12.2	mV		
TWFS integration time	0.0	0.0093	sec	107.26	Hz
TWFS guide star search radius	0.0	5.6	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Gal Cen**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			59 nm	60	Subaps
Bandwidth Error			87 nm	**51**	Hz (-3db)
High-order Measurement Error			79 nm	50	W
LGS Tomography Error			61 nm	4	sci beacon(s)
Asterism Deformation Error			25 nm	0.50	m LLT
Chromatic Error			2 nm		Upper limit
Dispersion Displacement Error			6 nm		Estimate
Multispectral Error			34 nm	50	zen; sci wav
Scintillation Error	*H*		20 nm	0.59	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		153 nm			
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			34 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			30 nm		Allocation
Residual Na Layer Focus Change			3 nm	30	m/s Na layer vel
DM Finite Stroke Errors			5 nm	5.3	um P-P stroke
DM Hysteresis			13 nm		from TMT model
High-Order Aliasing Error			19 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			33 nm		Allocation
Uncorrectable Instrument Aberrations			30 nm		DAVINCI
DM-to-lenslet Misregistration			15 nm		Allocation
DM-to-lenslet Pupil Scale Error			15 nm		Allocation
		92 nm			
Angular Anisoplanatism Error			24 nm	1.0	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		179 nm	**186 nm**	**High Order Strehl**	

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.03	0.09	0.17	0.28	0.42	0.60	0.76

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		0.14 mas	2 nm	**12.2**	mag (mV)
Tilt Bandwidth Error (one-axis)		0.21 mas	4 nm	**50.0**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.50 mas	9 nm	**5.6**	arcsec from sci
Residual Centroid Anisoplanatism		0.64 mas	11 nm	20	x reduction
Residual Atmospheric Dispersion	*H*	0.53 mas	10 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.01 mas	0 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		0.23 mas	4 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	145 nm		Allocation
Total Tip/Tilt Error (one-axis)		**2.2 mas**	42 nm	**Tip/Tilt Strehl**	
Total Effective Wavefront Error			**190 nm**	**Total Strehl (%)**	

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.64	0.76	0.84	0.89	0.92	0.94	0.96	0.97	0.99
Total Strehl (%)	0.00	0.00	0.02	0.08	0.16	0.26	0.40	0.59	0.75
FWHM (mas)	7.1	9.1	11.8	14.3	16.8	19.6	23.7	30.9	41.5

Ensquared Energy (*H*)	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		44
	Square	0.11	0.39	0.53	0.60	0.61	0.62	0.67	0.73	0.84		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage		
Galactic Latitude	0 deg	
Corresponding Sky Coverage	**0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	50	deg
r0	0.123	m
theta0_eff	1.331	arcsec
Wind Speed	14.78	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2

AO Modes of Operation	
Science AO Mode:	MOAO
LOWFS AO Mode:	Indep PnS

Number of WFS's for TT measurement	
TT	2
TTFA	1
3x3	0
HOWFS	0

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.37		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.8	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.28		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	IRS7		
Max TT Rejection Bandwidth	100	Hz	

Observation Parameters		
Max Exposure Time	10	sec

LO WFS Magnitudes								
111.2	111.2	111.2	111.2	111.2	111.2	11.2	7.0	4.6

Derived Values		
HO WFS Rate	1023	Hz
Detected PDE/subap/exp	48	
LO WFS Rate	2000	Hz
Detected PDE/subap/exp	21156	

Galactic Center Spectra

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	48	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	1023	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	12.2	mV	4.60	mKs
TT integration time	0.00050	0.0005	sec	2000	Hz
TT guide star distance	0.0	5.6	arcsec		
TWFS guide star birghtness	LGS	12.2	mV		
TWFS integration time	0.0	0.0094	sec	106.84	Hz
TWFS guide star search radius	0.0	5.6	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N		
Optimize LGS Range Gate?	N		
Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Gal Cen Spectra**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			59 nm	60	Subaps
Bandwidth Error			87 nm	**51**	Hz (-3db)
High-order Measurement Error			79 nm	50	W
LGS Tomography Error			61 nm	4	sci beacon(s)
Asterism Deformation Error			25 nm	0.50	m LLT
Chromatic Error			2 nm		Upper limit
Dispersion Displacement Error			6 nm		Estimate
Multispectral Error			34 nm	50	zen; sci wav
Scintillation Error	*H*		20 nm	0.59	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		153 nm			
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			34 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			30 nm		Allocation
Residual Na Layer Focus Change			3 nm	30	m/s Na layer vel
DM Finite Stroke Errors			5 nm	5.3	um P-P stroke
DM Hysteresis			13 nm		from TMT model
High-Order Aliasing Error			19 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			33 nm		Allocation
Uncorrectable Instrument Aberrations			30 nm		DAVINCI
DM-to-lenslet Misregistration			15 nm		Allocation
DM-to-lenslet Pupil Scale Error			15 nm		Allocation
		92 nm			
Angular Anisoplanatism Error			44 nm	2.0	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		179 nm	**189 nm**	**High Order Strehl**	

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.02	0.08	0.16	0.27	0.41	0.59	0.75

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		0.14 mas	2 nm	**12.2**	mag (mV)
Tilt Bandwidth Error (one-axis)		0.21 mas	4 nm	**50.0**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.50 mas	9 nm	**5.6**	arcsec from sci
Residual Centroid Anisoplanatism		0.64 mas	11 nm	20	x reduction
Residual Atmospheric Dispersion	*H*	0.53 mas	10 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.80 mas	14 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		0.23 mas	4 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	145 nm		Allocation
Total Tip/Tilt Error (one-axis)		**2.4 mas**	44 nm	**Tip/Tilt Strehl**	
Total Effective Wavefront Error			**194 nm**	**Total Strehl (%)**	

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.61	0.73	0.83	0.88	0.91	0.93	0.95	0.97	0.98
Total Strehl (%)	0.00	0.00	0.02	0.07	0.15	0.25	0.39	0.57	0.74
FWHM (mas)	7.1	9.1	11.8	14.3	16.8	19.6	23.7	30.9	41.5

Ensquared Energy	Sci Filter		Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		44
	H		Square	0.11	0.39	0.52	0.59	0.60	0.61	0.66	0.73	0.84		0.50
			Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage			
	Galactic Latitude	0 deg	
Corresponding Sky Coverage		**0%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	50	deg
r0	0.123	m
theta0_eff	1.331	arcsec
Wind Speed	14.78	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.37		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.8	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.28		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	IRS7		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	900	sec	

LO WFS Magnitudes								
111.2	111.2	111.2	111.2	111.2	111.2	11.2	7.0	4.6

Derived Values		
HO WFS Rate	1023	Hz
Detected PDE/subap/exp	48	
LO WFS Rate	2000	Hz
Detected PDE/subap/exp	21156	

Exo-planets

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings					
HO guide star brightness	LGS		mV	53	PDE/subap/exp	Optimize LGS Off-Pointing?	N		
Optim HO integration time:	0.00050	0.0010	sec	1023	Hz	Optimize LGS Range Gate?	N		
Optim subaperture width:	0.174	0.174	meters	60	Subaps	Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
TT guide star brightness	LGS	16.0	mV	13.40	mKs				
TT integration time	0.00050	0.0005	sec	2000	Hz				
TT guide star distance	0.0	0.0	arcsec						
TWFS guide star birghtness	LGS	16.0	mV						
TWFS integration time	0.0	2.0000	sec	0.50	Hz				
TWFS guide star search radius	0.0	0.0	arcsec						
Number of laser beacons		4.0							
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS		Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Exo-planets**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			50 nm	60	Subaps
Bandwidth Error			59 nm	**51**	Hz (-3db)
High-order Measurement Error			70 nm	50	W
LGS Tomography Error			37 nm	4	sci beacon(s)
Asterism Deformation Error			16 nm	0.50	m LLT
Chromatic Error			2 nm		Upper limit
Dispersion Displacement Error			2 nm		Estimate
Multispectral Error			25 nm	30	zen; sci wav
Scintillation Error	*H*		12 nm	0.34	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		116 nm			
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			34 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			30 nm		Allocation
Residual Na Layer Focus Change			32 nm	30	m/s Na layer vel
DM Finite Stroke Errors			6 nm	5.3	um P-P stroke
DM Hysteresis			13 nm		from TMT model
High-Order Aliasing Error			17 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			33 nm		Allocation
Uncorrectable Instrument Aberrations			30 nm		DAVINCI
DM-to-lenslet Misregistration			15 nm		Allocation
DM-to-lenslet Pupil Scale Error			15 nm		Allocation
		97 nm			
Angular Anisoplanatism Error			16 nm	1.0	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		151 nm	**158 nm**	**High Order Strehl**	

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		7.50 mas	121 nm	**18.3**	mag (mV)
Tilt Bandwidth Error (one-axis)		0.25 mas	4 nm	**50.0**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	**0.0**	arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20	x reduction
Residual Atmospheric Dispersion	*H*	0.26 mas	5 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.27 mas	5 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		0.23 mas	4 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	145 nm		Allocation
Total Tip/Tilt Error (one-axis)		**7.8 mas**	136 nm	**Tip/Tilt Strehl**	

Total Effective Wavefront Error **207 nm**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.08	0.18	0.29	0.40	0.54	0.70	0.82
Tip/Tilt Strehl	0.13	0.20	0.31	0.40	0.48	0.56	0.65	0.76	0.85
Total Strehl (%)	0.00	0.00	0.02	0.07	0.14	0.22	0.35	0.53	0.70
FWHM (mas)	10.3	11.8	14.0	16.1	18.4	20.9	24.8	31.8	42.2

Ensquared Energy *H*	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		36
	Square	0.13	0.45	0.61	0.69	0.71	0.72	0.75	0.80	0.86		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage Galactic Latitude 30 deg

Corresponding Sky Coverage **0%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters			System Parameters			LO WFS Magnitudes		
Zenith Angle	30	deg	LGS Asterism Radius	0.17	arcmin	19.3 18.6 17.6 16.8 16.5 16.1 15.6 14.5 13.4		
r0	0.147	m	LGS Power	50	W			
theta0_eff	2.145	arcsec	BTO Transmission	0.60		**Derived Values**		
Wind Speed	10.97	m/s	HO WFS Transmission	0.38		HO WFS Rate	1023	Hz
Outer Scale	50	m	HO WFS Type	SH	using CCID74	Detected PDE/subap/exp	53	
Sodium Abundance	3	x 109 cm-2	HO WFS Noise	1.8	e- rms			
			HO WFS Anti-aliasing	NO				
AO Modes of Operation			LO WFS Transmission	0.29		LO WFS Rate	2000	Hz
Science AO Mode:	MOAO		LO WFS Type	SH	using H2RG	Detected PDE/subap/exp	31	
LOWFS AO Mode:	Indep PnS		LO WFS Noise	3.2	e- rms			
			LO WFS Star Type:	M				
Number of WFS's for TT measurement			Max TT Rejection Bandwidth	100	Hz			
TT	2							
TTFA	1		**Observation Parameters**					
3x3	0		Max Exposure Time	300	sec			
HOWFS	0							

Minor Planets

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	57	PDE/subap/exp
Optim HO integration time:	0.00050	0.0011	sec	951	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	18.6	mV	13.73	mKs
TT integration time	0.00050	0.0025	sec	400	Hz
TT guide star distance	0.0	46.8	arcsec		
TWFS guide star birghtness	LGS	18.6	mV		
TWFS integration time	0.0	6.7694	sec	0.15	Hz
TWFS guide star search radius	0.0	46.8	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Minor Planets**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error		50 nm	60	Subaps
Bandwidth Error		61 nm	**48**	Hz (-3db)
High-order Measurement Error		66 nm	50	W
LGS Tomography Error		37 nm	4	sci beacon(s)
Asterism Deformation Error		16 nm	0.50	m LLT
Chromatic Error		3 nm		Upper limit
Dispersion Displacement Error		8 nm		Estimate
Multispectral Error		22 nm	30	zen; sci wav
Scintillation Error	Z	16 nm	0.34	Scint index at 0.5um
WFS Scintillation Error		10 nm		Allocation
	115 nm			
Uncorrectable Static Telescope Aberrations		43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations		37 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm		Allocation
Dynamic WFS Zero-point Calibration Error		25 nm		Allocation
Leaky Integrator Zero-point Calibration Error		10 nm		Allocation
Stale Reconstructor Error		15 nm		Allocation
Go-to Control Errors		30 nm		Allocation
Residual Na Layer Focus Change		39 nm	30	m/s Na layer vel
DM Finite Stroke Errors		6 nm	5.3	um P-P stroke
DM Hysteresis		13 nm		from TMT model
High-Order Aliasing Error		17 nm	60	Subaps
DM Drive Digitization		1 nm	16	bits
Uncorrectable AO System Aberrations		33 nm		Allocation
Uncorrectable Instrument Aberrations		30 nm		DAVINCI
DM-to-lenslet Misregistration		15 nm		Allocation
DM-to-lenslet Pupil Scale Error		15 nm		Allocation
	100 nm			
Angular Anisoplanatism Error		0 nm	0.0	arcsec
HO Wavefront Error Margin		45 nm		Allocation
Total High Order Wavefront Error	152 nm	**159 nm**	**High Order Strehl**	

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.08	0.17	0.29	0.40	0.54	0.69	0.82

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		2.42 mas	40 nm	**18.6**	mag (mV)
Tilt Bandwidth Error (one-axis)		0.74 mas	13 nm	**16.7**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		3.60 mas	59 nm	**46.8**	arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20	x reduction
Residual Atmospheric Dispersion	Z	0.68 mas	13 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.11 mas	2 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		0.70 mas	12 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	78 nm		Allocation
Total Tip/Tilt Error (one-axis)		**5.0 mas**	85 nm	**Tip/Tilt Strehl**	
Total Effective Wavefront Error			**179 nm**	**Total Strehl (%)**	

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.27	0.39	0.53	0.62	0.69	0.76	0.82	0.89	0.93
Total Strehl (%)	0.00	0.00	0.04	0.11	0.20	0.30	0.44	0.62	0.76
FWHM (mas)	8.3	10.1	12.6	14.9	17.3	20.0	24.1	31.2	41.7

Spaxel / Aperture Diameter (mas)		15	35	50	70	90	120	240	400	800		370
Ensquared Energy Z	Square	0.15	0.28	0.29	0.30	0.31	0.32	0.40	0.51	0.69		0.50
	Seeing-Limited	0.00	0.00	0.01	0.01	0.02	0.04	0.14	0.34	0.81		

Sky Coverage	Galactic Latitude	60 deg	
Corresponding Sky Coverage		**30%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	120	sec	

LO WFS Magnitudes								
19.6	18.9	18.0	17.1	16.8	16.4	15.9	14.8	13.7

Derived Values		
HO WFS Rate	951	Hz
Detected PDE/subap/exp	57	
LO WFS Rate	400	Hz
Detected PDE/subap/exp	113	

Io

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	5.00		mV	2110	PDE/subap/exp
Optim HO integration time:	0.00050	0.0011	sec	2000	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	5.0	18.6	mV	3.48	mKs
TT integration time	0.00050	0.0025	sec	2000	Hz
TT guide star distance	0.0	46.8	arcsec		
TWFS guide star birghtness	5.0	18.6	mV		
TWFS integration time	0.0	6.7694	sec	2000.00	Hz
TWFS guide star search radius	0.0	46.8	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N		
Optimize LGS Range Gate?	N		
Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: NGAO NGS
Instrument: DAVINCI
Sci. Observation Io

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (NGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		50 nm	60 Subaps
Bandwidth Error		40 nm	**100** Hz (-3db)
High-order Measurement Error		10 nm	5 mV
LGS Tomography Error		0 nm	1 natural guide star
Asterism Deformation Error		0 nm	0.50 m LLT
Chromatic Error		1 nm	Upper limit
Dispersion Displacement Error		19 nm	Estimate
Multispectral Error		22 nm	30 zen; sci wav
Scintillation Error	*Z*	16 nm	0.34 Scint index at 0.5um
WFS Scintillation Error		10 nm	Allocation
	74 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations		17 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Allocation
Dynamic WFS Zero-point Calibration Error		20 nm	Allocation
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation
Stale Reconstructor Error		15 nm	Allocation
Go-to Control Errors		0 nm	Allocation
Residual Na Layer Focus Change		0 nm	30 m/s Na layer vel
DM Finite Stroke Errors		8 nm	5.3 um P-P stroke
DM Hysteresis		13 nm	from TMT model
High-Order Aliasing Error		11 nm	60 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		25 nm	Allocation
Uncorrectable Instrument Aberrations		30 nm	DAVINCI
DM-to-lenslet Misregistration		15 nm	Allocation
DM-to-lenslet Pupil Scale Error		15 nm	Allocation
	76 nm		
Angular Anisoplanatism Error		9 nm	0.5 arcsec
HO Wavefront Error Margin		45 nm	Allocation
Total High Order Wavefront Error	106 nm	**116 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.08	0.27	0.41	0.53	0.63	0.73	0.83	0.90

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.17 mas	3 nm	**5.0** mag (mV)
Tilt Bandwidth Error (one-axis)		0.25 mas	4 nm	**50.0** Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	**0.0** arcsec from sci
Residual Centroid Anisoplanatism		0.00 mas	0 nm	NGS x reduction
Residual Atmospheric Dispersion	*Z*	0.68 mas	13 nm	20 x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height
Non-Common-Path Tip-Tilt Errors		0.01 mas	0 nm	3.2 mas/l Allocation
Residual Telescope Pointing Jitter (one-axis)		0.23 mas	4 nm	29 Hz input disturbance
TT Error Margin		2.00 mas	78 nm	Allocation
Total Tip/Tilt Error (one-axis)		**2.1 mas**	39 nm	**Tip/Tilt Strehl**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.66	0.77	0.86	0.90	0.92	0.94	0.96	0.98	0.99

Total Effective Wavefront Error	**119 nm**	**Total Strehl (%)**	0.00	0.06	0.23	0.37	0.49	0.59	0.70	0.81	0.89
		FWHM (mas)	7.0	9.1	11.8	14.2	16.8	19.5	23.6	30.9	41.5

			Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		30
Ensquared Energy	*Z*		Square	0.27	0.51	0.53	0.54	0.54	0.55	0.62	0.70	0.83		0.50
			Seeing-Limited	0.00	0.00	0.01	0.01	0.02	0.04	0.14	0.34	0.81		

Sky Coverage	Galactic Latitude	N/A	deg
Corresponding Sky Coverage		**N/A**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2

AO Modes of Operation	
Science AO Mode:	SCAO
LOWFS AO Mode:	0.00

Number of WFS's for TT measurement	
TT	0
TTFA	0
3x3	0
HOWFS	1

System Parameters			
LGS Asterism Radius	0.00	arcmin	
LGS Power	NGS	W	
BTO Transmission	1.00		
HO WFS Transmission	0.24		
HO WFS Type	SH	using	CCID74
HO WFS Noise	2.6	e- rms	
HO WFS Anti-aliasing	YES		
LO WFS Transmission	0.24		
LO WFS Type	NGS	using	CCID74
LO WFS Noise	2.6	e- rms	
LO WFS Star Type:	G		
Max TT Rejection Bandwidth	100	Hz	

Observation Parameters		
Max Exposure Time	10	sec

LO WFS Magnitudes								
6.1	4.7	4.3	4.2	4.1	4.0	3.8	3.5	3.5

Derived Values		
HO WFS Rate	2000	Hz
Detected PDE/subap/exp	2110	
LO WFS Rate	2000	Hz
Detected PDE/subap/exp	######	

QSO Host Galaxies

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings			
HO guide star brightness	LGS		mV	56	PDE/subap/exp	Optimize LGS Off-Pointing?	N
Optim HO integration time:	0.00050	0.0010	sec	958	Hz	Optimize LGS Range Gate?	N
Optim subaperture width:	0.174	0.174	meters	60	Subaps	Optimize Subap Diameter?	N 0.182 m Non-optim subap width
TT guide star brightness	LGS	8.0	mV	-4.90	mKs		
TT integration time	0.00050	0.0005	sec	2000	Hz		
TT guide star distance	0.0	0.0	arcsec				
TWFS guide star birghtness	LGS	8.0	mV				
TWFS integration time	0.0	0.0040	sec	249.75	Hz		
TWFS guide star search radius	0.0	0.0	arcsec				
Number of laser beacons		4.0					
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS		Optimize LGS asterism radius?	N <-- not yet implemented (11/18/08)

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **QSO Host Galaxies**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratio (%)
Atmospheric Fitting Error		50 nm	60 Subaps	
Bandwidth Error		61 nm	**48** Hz (-3db)	
High-order Measurement Error		64 nm	50 W	
LGS Tomography Error		37 nm	4 sci beacon(s)	
Asterism Deformation Error		16 nm	0.50 m LLT	
Chromatic Error		2 nm	Upper limit	
Dispersion Displacement Error		2 nm	Estimate	
Multispectral Error		25 nm	30 zen; sci wav	
Scintillation Error	*H*	12 nm	0.34 Scint index at 0.5um	
WFS Scintillation Error		10 nm	Allocation	
	113 nm			
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts Across Pupil	
Uncorrectable Dynamic Telescope Aberrations		36 nm	Dekens Ph.D	
Static WFS Zero-point Calibration Error		25 nm	Allocation	
Dynamic WFS Zero-point Calibration Error		25 nm	Allocation	
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation	
Stale Reconstructor Error		15 nm	Allocation	
Go-to Control Errors		30 nm	Allocation	
Residual Na Layer Focus Change		1 nm	30 m/s Na layer vel	
DM Finite Stroke Errors		6 nm	5.3 um P-P stroke	
DM Hysteresis		13 nm	from TMT model	
High-Order Aliasing Error		17 nm	60 Subaps	
DM Drive Digitization		1 nm	16 bits	
Uncorrectable AO System Aberrations		33 nm	Allocation	
Uncorrectable Instrument Aberrations		30 nm	DAVINCI	
DM-to-lenslet Misregistration		15 nm	Allocation	
DM-to-lenslet Pupil Scale Error		15 nm	Allocation	
	92 nm			
Angular Anisoplanatism Error		16 nm	1.0 arcsec	
HO Wavefront Error Margin		45 nm	Allocation	

Total High Order Wavefront Error	146 nm	154 nm	High Order Strehl	u'	g'	r'	i'	Z	Y	J	H	K
				0.00	0.01	0.09	0.20	0.31	0.43	0.56	0.71	0.83

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%)
Tilt Measurement Error (one-axis)		0.00 mas	0 nm	**0.0** mag (mV)	
Tilt Bandwidth Error (one-axis)		0.25 mas	4 nm	**50.0** Hz (-3db)	
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	**0.0** arcsec from sci	
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20 x reduction	
Residual Atmospheric Dispersion	*H*	0.26 mas	5 nm	20 x reduction	
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height	
Non-Common-Path Tip-Tilt Errors		0.80 mas	14 nm	3.2 mas/l Allocation	
Residual Telescope Pointing Jitter (one-axis)		0.23 mas	4 nm	29 Hz input disturbance	
TT Error Margin		2.00 mas	145 nm	Allocation	

			u'	g'	r'	i'	Z	Y	J	H	K
Total Tip/Tilt Error (one-axis)	2.3 mas	42 nm Tip/Tilt Strehl	0.64	0.75	0.84	0.89	0.92	0.94	0.96	0.97	0.99
Total Effective Wavefront Error	157 nm	Total Strehl (%)	0.00	0.01	0.08	0.17	0.28	0.40	0.54	0.69	0.82
		FWHM (mas)	7.1	9.1	11.8	14.3	16.8	19.6	23.7	30.9	41.5

Spaxel / Aperture Diameter (mas)		15	35	50	70	90	120	240	400	800		36
Ensquared Energy *H*	Square	0.13	0.46	0.62	0.71	0.72	0.73	0.76	0.80	0.86		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage	Galactic Latitude	60 deg	
Corresponding Sky Coverage		0%	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters			System Parameters			
Zenith Angle	30	deg	LGS Asterism Radius	0.17	arcmin	
r0	0.147	m	LGS Power	50	W	
theta0_eff	2.145	arcsec	BTO Transmission	0.60		
Wind Speed	10.97	m/s	HO WFS Transmission	0.38		
Outer Scale	50	m	HO WFS Type	SH	using	CCID74
Sodium Abundance	3	x 109 cm-2	HO WFS Noise	1.7	e- rms	
			HO WFS Anti-aliasing	NO		
AO Modes of Operation			LO WFS Transmission	0.29		
Science AO Mode:	MOAO		LO WFS Type	SH	using	H2RG
LOWFS AO Mode:	Indep PnS		LO WFS Noise	3.2	e- rms	
			LO WFS Star Type:	M		
Number of WFS's for TT measurement			Max TT Rejection Bandwidth	100	Hz	
TT	2					
TTFA	1		**Observation Parameters**			
3x3	0		Max Exposure Time	900	sec	
HOWFS	0					

LO WFS Magnitudes								
1.0	0.3	-0.7	-1.5	-1.8	-2.2	-2.7	-3.8	-4.9

Derived Values		
HO WFS Rate	958	Hz
Detected PDE/subap/exp	56	
LO WFS Rate	2000	Hz
Detected PDE/subap/exp	######	

Gravitational Lensing

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	57	PDE/subap/exp
Optim HO integration time:	0.00050	0.0011	sec	949	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	18.7	mV	13.84	mKs
TT integration time	0.00050	0.0031	sec	324	Hz
TT guide star distance	0.0	45.3	arcsec		
TWFS guide star birghtness	LGS	18.7	mV		
TWFS integration time	0.0	5.6116	sec	0.18	Hz
TWFS guide star search radius	0.0	45.3	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N		
Optimize LGS Range Gate?	N		
Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Gravitational Lensing**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter
Atmospheric Fitting Error			50 nm	60 Subaps
Bandwidth Error			61 nm	**47** Hz (-3db)
High-order Measurement Error			66 nm	50 W
LGS Tomography Error			37 nm	4 sci beacon(s)
Asterism Deformation Error			16 nm	0.50 m LLT
Chromatic Error			2 nm	Upper limit
Dispersion Displacement Error			2 nm	Estimate
Multispectral Error			25 nm	30 zen; sci wav
Scintillation Error	*H*		12 nm	0.34 Scint index at 0.5um
WFS Scintillation Error			10 nm	Allocation
		115 nm		
Uncorrectable Static Telescope Aberrations			43 nm	64 Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			37 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm	Allocation
Dynamic WFS Zero-point Calibration Error			25 nm	Allocation
Leaky Integrator Zero-point Calibration Error			10 nm	Allocation
Stale Reconstructor Error			15 nm	Allocation
Go-to Control Errors			30 nm	Allocation
Residual Na Layer Focus Change			38 nm	30 m/s Na layer vel
DM Finite Stroke Errors			6 nm	5.3 um P-P stroke
DM Hysteresis			13 nm	from TMT model
High-Order Aliasing Error			17 nm	60 Subaps
DM Drive Digitization			1 nm	16 bits
Uncorrectable AO System Aberrations			33 nm	Allocation
Uncorrectable Instrument Aberrations			32 nm	DAVINCI
DM-to-lenslet Misregistration			15 nm	Allocation
DM-to-lenslet Pupil Scale Error			15 nm	Allocation
		100 nm		
Angular Anisoplanatism Error			63 nm	5.0 arcsec
HO Wavefront Error Margin			45 nm	Allocation
Total High Order Wavefront Error		152 nm	**171 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.05	0.13	0.23	0.35	0.49	0.66	0.79

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		2.22 mas	38 nm	**18.7** mag (mV)
Tilt Bandwidth Error (one-axis)		0.88 mas	15 nm	**13.9** Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		3.48 mas	59 nm	**45.3** arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20 x reduction
Residual Atmospheric Dispersion	*H*	0.26 mas	5 nm	20 x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height
Non-Common-Path Tip-Tilt Errors		1.60 mas	27 nm	3.2 mas/l Allocation
Residual Telescope Pointing Jitter (one-axis)		0.83 mas	14 nm	29 Hz input disturbance
TT Error Margin		2.00 mas	145 nm	Allocation
Total Tip/Tilt Error (one-axis)		**5.0 mas**	92 nm	**Tip/Tilt Strehl**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.26	0.38	0.52	0.61	0.69	0.75	0.82	0.88	0.93
Total Effective Wavefront Error 192 nm — Total Strehl (%)	0.00	0.00	0.03	0.08	0.16	0.26	0.40	0.58	0.74
FWHM (mas)	8.4	10.1	12.7	14.9	17.4	20.1	24.1	31.2	41.8

Ensquared Energy *H*	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		36
	Square	0.12	0.43	0.58	0.65	0.67	0.68	0.72	0.78	0.86		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage

Galactic Latitude 60 deg

Corresponding Sky Coverage **30%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	1800	sec	

LO WFS Magnitudes								
19.7	19.0	18.1	17.2	16.9	16.6	16.0	14.9	13.8

Derived Values		
HO WFS Rate	949	Hz
Detected PDE/subap/exp	57	
LO WFS Rate	324	Hz
Detected PDE/subap/exp	126	

Astrometry Science

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings						
HO guide star brightness	LGS		mV	57	PDE/subap/exp	Optimize LGS Off-Pointing?	N			
Optim HO integration time:	0.00050	0.0011	sec	948	Hz	Optimize LGS Range Gate?	N			
Optim subaperture width:	0.174	0.174	meters	60	Subaps	Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
TT guide star brightness	LGS	19.0	mV	14.08	mKs					
TT integration time	0.00050	0.0045	sec	221	Hz					
TT guide star distance	0.0	42.4	arcsec							
TWFS guide star birghtness	LGS	19.0	mV							
TWFS integration time	0.0	4.4488	sec	0.22	Hz					
TWFS guide star search radius	0.0	42.4	arcsec							
Number of laser beacons		4.0								
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS		Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Astrometry Science**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			50 nm	60	Subaps
Bandwidth Error			61 nm	**47**	Hz (-3db)
High-order Measurement Error			66 nm	50	W
LGS Tomography Error			37 nm	4	sci beacon(s)
Asterism Deformation Error			16 nm	0.50	m LLT
Chromatic Error			2 nm		Upper limit
Dispersion Displacement Error			2 nm		Estimate
Multispectral Error			25 nm	30	zen; sci wav
Scintillation Error	*H*		12 nm	0.34	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		115 nm			
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			37 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			25 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			30 nm		Allocation
Residual Na Layer Focus Change			39 nm	30	m/s Na layer vel
DM Finite Stroke Errors			6 nm	5.3	um P-P stroke
DM Hysteresis			13 nm		from TMT model
High-Order Aliasing Error			17 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			33 nm		Allocation
Uncorrectable Instrument Aberrations			32 nm		DAVINCI
DM-to-lenslet Misregistration			15 nm		Allocation
DM-to-lenslet Pupil Scale Error			15 nm		Allocation
		101 nm			
Angular Anisoplanatism Error			63 nm	5.0	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		153 nm	**171 nm**	**High Order Strehl**	

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.05	0.13	0.23	0.35	0.49	0.66	0.79

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		1.96 mas	33 nm	**19.0**	mag (mV)
Tilt Bandwidth Error (one-axis)		1.24 mas	21 nm	**10.0**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		3.26 mas	55 nm	**42.4**	arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20	x reduction
Residual Atmospheric Dispersion	*H*	0.26 mas	5 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.03 mas	0 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		1.16 mas	20 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	145 nm		Allocation
Total Tip/Tilt Error (one-axis)		**4.7 mas**	85 nm	**Tip/Tilt Strehl**	
Total Effective Wavefront Error			**189 nm**	**Total Strehl (%)**	

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.29	0.42	0.56	0.65	0.72	0.78	0.84	0.90	0.94
Total Strehl (%)	0.00	0.00	0.03	0.09	0.17	0.27	0.41	0.59	0.75
FWHM (mas)	8.2	10.0	12.5	14.8	17.3	20.0	24.0	31.2	41.7

Spaxel / Aperture Diameter (mas)		15	35	50	70	90	120	240	400	800		36
Ensquared Energy *H*	Square	0.12	0.43	0.57	0.65	0.67	0.68	0.72	0.78	0.86		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage	Galactic Latitude	60 deg	
Corresponding Sky Coverage		**30%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	30	sec	

LO WFS Magnitudes								
20.0	19.3	18.3	17.5	17.2	16.8	16.3	15.2	14.1

Derived Values		
HO WFS Rate	948	Hz
Detected PDE/subap/exp	57	
LO WFS Rate	221	Hz
Detected PDE/subap/exp	149	

Transients

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	56	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	954	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	17.0	mV	12.09	mKs
TT integration time	0.00050	0.0020	sec	508	Hz
TT guide star distance	0.0	60.0	arcsec		
TWFS guide star birghtness	LGS	17.0	mV		
TWFS integration time	0.0	0.1710	sec	5.85	Hz
TWFS guide star search radius	0.0	60.0	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Transients**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		50 nm	60 Subaps
Bandwidth Error		61 nm	**48** Hz (-3db)
High-order Measurement Error		66 nm	50 W
LGS Tomography Error		37 nm	4 sci beacon(s)
Asterism Deformation Error		16 nm	0.50 m LLT
Chromatic Error		3 nm	Upper limit
Dispersion Displacement Error		8 nm	Estimate
Multispectral Error		22 nm	30 zen; sci wav
Scintillation Error	Z	16 nm	0.34 Scint index at 0.5um
WFS Scintillation Error		10 nm	Allocation
	115 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations		36 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Allocation
Dynamic WFS Zero-point Calibration Error		25 nm	Allocation
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation
Stale Reconstructor Error		15 nm	Allocation
Go-to Control Errors		30 nm	Allocation
Residual Na Layer Focus Change		19 nm	30 m/s Na layer vel
DM Finite Stroke Errors		6 nm	5.3 um P-P stroke
DM Hysteresis		13 nm	from TMT model
High-Order Aliasing Error		17 nm	60 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		33 nm	Allocation
Uncorrectable Instrument Aberrations		30 nm	DAVINCI
DM-to-lenslet Misregistration		15 nm	Allocation
DM-to-lenslet Pupil Scale Error		15 nm	Allocation
	94 nm		
Angular Anisoplanatism Error		16 nm	1.0 arcsec
HO Wavefront Error Margin		45 nm	Allocation
Total High Order Wavefront Error	148 nm	**156 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.08	0.19	0.30	0.41	0.55	0.70	0.82

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.94 mas	16 nm	**17.0** mag (mV)
Tilt Bandwidth Error (one-axis)		0.61 mas	10 nm	**20.2** Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	**0.0** arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20 x reduction
Residual Atmospheric Dispersion	Z	0.68 mas	13 nm	20 x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height
Non-Common-Path Tip-Tilt Errors		0.80 mas	14 nm	3.2 mas/l Allocation
Residual Telescope Pointing Jitter (one-axis)		0.57 mas	10 nm	29 Hz input disturbance
TT Error Margin		2.00 mas	78 nm	Allocation
Total Tip/Tilt Error (one-axis)		**2.6 mas**	48 nm	**Tip/Tilt Strehl**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.56	0.69	0.80	0.85	0.89	0.92	0.94	0.96	0.98

			u'	g'	r'	i'	Z	Y	J	H	K
Total Effective Wavefront Error	**162 nm**	**Total Strehl (%)**	0.00	0.01	0.07	0.16	0.27	0.38	0.52	0.68	0.81
		FWHM (mas)	7.2	9.2	11.9	14.3	16.8	19.6	23.7	30.9	41.5

	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		380
Ensquared Energy Z	Square	0.15	0.29	0.31	0.31	0.32	0.33	0.40	0.51	0.68		0.50
	Seeing-Limited	0.00	0.00	0.01	0.01	0.02	0.04	0.14	0.34	0.81		

Sky Coverage Galactic Latitude 40 deg

Corresponding Sky Coverage **30%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2

AO Modes of Operation	
Science AO Mode:	MOAO
LOWFS AO Mode:	Indep PnS

Number of WFS's for TT measurement	
TT	2
TTFA	1
3x3	0
HOWFS	0

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.7	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	

Observation Parameters		
Max Exposure Time	900	sec

LO WFS Magnitudes								
18.0	17.3	16.3	15.5	15.2	14.8	14.3	13.2	12.1

Derived Values		
HO WFS Rate	954	Hz
Detected PDE/subap/exp	56	
LO WFS Rate	508	Hz
Detected PDE/subap/exp	411	

Resolved Stellar Populations

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	48	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	1020	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	18.7	mV	13.77	mKs
TT integration time	0.00050	0.0044	sec	226	Hz
TT guide star distance	0.0	46.3	arcsec		
TWFS guide star birghtness	LGS	18.7	mV		
TWFS integration time	0.0	6.2993	sec	0.16	Hz
TWFS guide star search radius	0.0	46.3	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation: **Resolved Stellar Populations**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter	Strehl Ratio (%) u'	g'	r'	i'	Z	Y	J	H	K
Atmospheric Fitting Error		59 nm	60 Subaps									
Bandwidth Error		87 nm	**51** Hz (-3db)									
High-order Measurement Error		80 nm	50 W									
LGS Tomography Error		61 nm	4 sci beacon(s)									
Asterism Deformation Error		25 nm	0.50 m LLT									
Chromatic Error		2 nm	Upper limit									
Dispersion Displacement Error		29 nm	Estimate									
Multispectral Error		22 nm	50 zen; sci wav									
Scintillation Error	I'	20 nm	0.59 Scint index at 0.5um									
WFS Scintillation Error		10 nm	Allocation									
	154 nm											
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts Across Pupil									
Uncorrectable Dynamic Telescope Aberrations		34 nm	Dekens Ph.D									
Static WFS Zero-point Calibration Error		25 nm	Allocation									
Dynamic WFS Zero-point Calibration Error		25 nm	Allocation									
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation									
Stale Reconstructor Error		15 nm	Allocation									
Go-to Control Errors		30 nm	Allocation									
Residual Na Layer Focus Change		54 nm	30 m/s Na layer vel									
DM Finite Stroke Errors		5 nm	5.3 um P-P stroke									
DM Hysteresis		13 nm	from TMT model									
High-Order Aliasing Error		19 nm	60 Subaps									
DM Drive Digitization		1 nm	16 bits									
Uncorrectable AO System Aberrations		33 nm	Allocation									
Uncorrectable Instrument Aberrations		32 nm	DAVINCI									
DM-to-lenslet Misregistration		15 nm	Allocation									
DM-to-lenslet Pupil Scale Error		15 nm	Allocation									
	107 nm											
Angular Anisoplanatism Error		94 nm	5.0 arcsec									
HO Wavefront Error Margin		45 nm	Allocation									
Total High Order Wavefront Error	188 nm	**215 nm**	**High Order Strehl**	0.00	0.00	0.01	0.04	0.10	0.18	0.31	0.51	0.69

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	Strehl ratios (%) u'	g'	r'	i'	Z	Y	J	H	K
Tilt Measurement Error (one-axis)		2.82 mas	46 nm	**18.7** mag (mV)									
Tilt Bandwidth Error (one-axis)		1.04 mas	18 nm	**10.1** Hz (-3db)									
Tilt Anisoplanatism Error (one-axis)		4.13 mas	65 nm	**46.3** arcsec from sci									
Residual Centroid Anisoplanatism		0.64 mas	11 nm	20 x reduction									
Residual Atmospheric Dispersion	I'	3.03 mas	54 nm	20 x reduction									
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height									
Non-Common-Path Tip-Tilt Errors		0.27 mas	5 nm	3.2 mas/l Allocation									
Residual Telescope Pointing Jitter (one-axis)		1.14 mas	19 nm	29 Hz input disturbance									
TT Error Margin		2.00 mas	66 nm	Allocation									
Total Tip/Tilt Error (one-axis)		**6.4 mas**	100 nm	**Tip/Tilt Strehl**	0.18	0.28	0.40	0.49	0.58	0.65	0.73	0.82	0.89

			u'	g'	r'	i'	Z	Y	J	H	K
Total Effective Wavefront Error	**236 nm**	**Total Strehl (%)**	0.00	0.00	0.00	0.02	0.06	0.12	0.23	0.42	0.62
		FWHM (mas)	9.3	10.9	13.3	15.5	17.8	20.5	24.4	31.5	41.9

		Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		560
Ensquared Energy	I'	Square	0.03	0.04	0.05	0.06	0.07	0.08	0.19	0.35	0.66		0.50
		Seeing-Limited	0.00	0.00	0.01	0.01	0.02	0.04	0.13	0.33	0.78		

Sky Coverage	Galactic Latitude	60 deg	
Corresponding Sky Coverage		**30%**	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	50	deg
r0	0.123	m
theta0_eff	1.331	arcsec
Wind Speed	14.78	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.37		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.8	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.28		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	300	sec	

LO WFS Magnitudes								
19.7	18.9	18.0	17.2	16.8	16.5	16.0	14.9	13.8

Derived Values		
HO WFS Rate	1020	Hz
Detected PDE/subap/exp	48	
LO WFS Rate	226	Hz
Detected PDE/subap/exp	134	

Debris Disks and YSOs

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here. How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	53	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	1020	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	18.0	mV	11.10	mKs
TT integration time	0.00050	0.0044	sec	226	Hz
TT guide star distance	0.0	60.0	arcsec		
TWFS guide star birghtness	LGS	18.0	mV		
TWFS integration time	0.0	2.0000	sec	0.50	Hz
TWFS guide star search radius	0.0	60.0	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N		
Optimize LGS Range Gate?	N		
Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation: **Debris Disks and YSOs**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		50 nm	60 Subaps
Bandwidth Error		59 nm	**51** Hz (-3db)
High-order Measurement Error		70 nm	50 W
LGS Tomography Error		37 nm	4 sci beacon(s)
Asterism Deformation Error		16 nm	0.50 m LLT
Chromatic Error		2 nm	Upper limit
Dispersion Displacement Error		11 nm	Estimate
Multispectral Error		16 nm	30 zen; sci wav
Scintillation Error	I'	12 nm	0.34 Scint index at 0.5um
WFS Scintillation Error		10 nm	Allocation
	114 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations		34 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Allocation
Dynamic WFS Zero-point Calibration Error		25 nm	Allocation
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation
Stale Reconstructor Error		15 nm	Allocation
Go-to Control Errors		30 nm	Allocation
Residual Na Layer Focus Change		30 nm	30 m/s Na layer vel
DM Finite Stroke Errors		6 nm	5.3 um P-P stroke
DM Hysteresis		13 nm	from TMT model
High-Order Aliasing Error		17 nm	60 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		33 nm	Allocation
Uncorrectable Instrument Aberrations		30 nm	DAVINCI
DM-to-lenslet Misregistration		15 nm	Allocation
DM-to-lenslet Pupil Scale Error		15 nm	Allocation
	96 nm		
Angular Anisoplanatism Error		16 nm	1.0 arcsec
HO Wavefront Error Margin		45 nm	Allocation
Total High Order Wavefront Error	149 nm	**157 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.08	0.18	0.29	0.41	0.54	0.70	0.82

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.32 mas	5 nm	**16.0** mag (mV)
Tilt Bandwidth Error (one-axis)		1.21 mas	21 nm	**10.1** Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	**0.0** arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20 x reduction
Residual Atmospheric Dispersion	I'	1.47 mas	27 nm	20 x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height
Non-Common-Path Tip-Tilt Errors		0.27 mas	5 nm	3.2 mas/l Allocation
Residual Telescope Pointing Jitter (one-axis)		1.14 mas	19 nm	29 Hz input disturbance
TT Error Margin		2.00 mas	66 nm	Allocation
Total Tip/Tilt Error (one-axis)		**3.1 mas**	55 nm	**Tip/Tilt Strehl**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.49	0.62	0.74	0.81	0.86	0.89	0.92	0.95	0.97

Total Effective Wavefront Error **165 nm**

	u'	g'	r'	i'	Z	Y	J	H	K
Total Strehl (%)	0.00	0.01	0.06	0.14	0.25	0.36	0.50	0.67	0.80
FWHM (mas)	7.4	9.3	12.0	14.4	16.9	19.7	23.7	31.0	41.6

Ensquared Energy (I')	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		510
	Square	0.11	0.18	0.19	0.19	0.20	0.22	0.30	0.42	0.63		0.50
	Seeing-Limited	0.00	0.00	0.01	0.01	0.02	0.04	0.13	0.33	0.78		

Sky Coverage Galactic Latitude 30 deg

Corresponding Sky Coverage **22%** This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2

AO Modes of Operation	
Science AO Mode:	MOAO
LOWFS AO Mode:	Indep PnS

Number of WFS's for TT measurement	
TT	2
TTFA	1
3x3	0
HOWFS	0

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.8	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	M		
Max TT Rejection Bandwidth	100	Hz	

Observation Parameters		
Max Exposure Time	300	sec

LO WFS Magnitudes								
17.0	16.3	15.3	14.5	14.2	13.8	13.3	12.2	11.1

Derived Values		
HO WFS Rate	1020	Hz
Detected PDE/subap/exp	53	
LO WFS Rate	226	Hz
Detected PDE/subap/exp	2560	

Gas Giant Planets

Optimizations/sky coverage calculations

COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	LGS		mV	53	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	1020	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	LGS	18.0	mV	3.48	mKs
TT integration time	0.00050	0.0044	sec	226	Hz
TT guide star distance	0.0	30.0	arcsec		
TWFS guide star birghtness	LGS	18.0	mV		
TWFS integration time	0.0	2.0000	sec	0.50	Hz
TWFS guide star search radius	0.0	30.0	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N		
Optimize LGS Range Gate?	N		
Optimize Subap Diameter?	N	0.182 m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)	

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO LGS**
Instrument: **DAVINCI**
Sci. Observation **Gas Giant Planets**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (LGS Mode)		Wavefront Error (rms)	Parameter
Atmospheric Fitting Error		50 nm	60 Subaps
Bandwidth Error		59 nm	**51** Hz (-3db)
High-order Measurement Error		68 nm	50 W
LGS Tomography Error		37 nm	4 sci beacon(s)
Asterism Deformation Error		16 nm	0.50 m LLT
Chromatic Error		1 nm	Upper limit
Dispersion Displacement Error		1 nm	Estimate
Multispectral Error		25 nm	30 zen; sci wav
Scintillation Error	*K*	12 nm	0.34 Scint index at 0.5um
WFS Scintillation Error		10 nm	Allocation
	115 nm		
Uncorrectable Static Telescope Aberrations		43 nm	64 Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations		34 nm	Dekens Ph.D
Static WFS Zero-point Calibration Error		25 nm	Allocation
Dynamic WFS Zero-point Calibration Error		25 nm	Allocation
Leaky Integrator Zero-point Calibration Error		10 nm	Allocation
Stale Reconstructor Error		15 nm	Allocation
Go-to Control Errors		30 nm	Allocation
Residual Na Layer Focus Change		33 nm	30 m/s Na layer vel
DM Finite Stroke Errors		6 nm	5.3 um P-P stroke
DM Hysteresis		13 nm	from TMT model
High-Order Aliasing Error		17 nm	60 Subaps
DM Drive Digitization		1 nm	16 bits
Uncorrectable AO System Aberrations		33 nm	Allocation
Uncorrectable Instrument Aberrations		32 nm	DAVINCI
DM-to-lenslet Misregistration		15 nm	Allocation
DM-to-lenslet Pupil Scale Error		15 nm	Allocation
	98 nm		
Angular Anisoplanatism Error		63 nm	5.0 arcsec
HO Wavefront Error Margin		45 nm	Allocation
Total High Order Wavefront Error	151 nm	**169 nm**	**High Order Strehl**

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.01	0.05	0.14	0.24	0.35	0.49	0.66	0.80

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter
Tilt Measurement Error (one-axis)		0.01 mas	0 nm	**5.0** mag (mV)
Tilt Bandwidth Error (one-axis)		1.21 mas	21 nm	**10.1** Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		2.31 mas	39 nm	**30.0** arcsec from sci
Residual Centroid Anisoplanatism		0.55 mas	9 nm	20 x reduction
Residual Atmospheric Dispersion	*K*	0.12 mas	2 nm	20 x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0 m conj height
Non-Common-Path Tip-Tilt Errors		0.00 mas	0 nm	3.2 mas/l Allocation
Residual Telescope Pointing Jitter (one-axis)		1.14 mas	20 nm	29 Hz input disturbance
TT Error Margin		2.00 mas	195 nm	Allocation
Total Tip/Tilt Error (one-axis)		**3.5 mas**	66 nm	**Tip/Tilt Strehl**
Total Effective Wavefront Error			**180 nm**	**Total Strehl (%)**

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.42	0.56	0.69	0.76	0.82	0.86	0.90	0.94	0.97
Total Strehl (%)	0.00	0.00	0.04	0.10	0.20	0.30	0.44	0.62	0.77
FWHM (mas)	7.6	9.5	12.1	14.5	17.0	19.7	23.8	31.0	41.6

	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		44
Ensquared Energy *K*	Square	0.09	0.35	0.55	0.73	0.79	0.81	0.84	0.87	0.91		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.20	0.45	0.90		

Sky Coverage Galactic Latitude N/A deg

Corresponding Sky Coverage ###### This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters		
Zenith Angle	30	deg
r0	0.147	m
theta0_eff	2.145	arcsec
Wind Speed	10.97	m/s
Outer Scale	50	m
Sodium Abundance	3	x 109 cm-2
AO Modes of Operation		
Science AO Mode:	MOAO	
LOWFS AO Mode:	Indep PnS	
Number of WFS's for TT measurement		
TT	2	
TTFA	1	
3x3	0	
HOWFS	0	

System Parameters			
LGS Asterism Radius	0.17	arcmin	
LGS Power	50	W	
BTO Transmission	0.60		
HO WFS Transmission	0.38		
HO WFS Type	SH	using	CCID74
HO WFS Noise	1.8	e- rms	
HO WFS Anti-aliasing	NO		
LO WFS Transmission	0.29		
LO WFS Type	SH	using	H2RG
LO WFS Noise	3.2	e- rms	
LO WFS Star Type:	G		
Max TT Rejection Bandwidth	100	Hz	
Observation Parameters			
Max Exposure Time	2	sec	

LO WFS Magnitudes								
6.1	4.7	4.3	4.2	4.1	4.0	3.8	3.5	3.5

Derived Values		
HO WFS Rate	1020	Hz
Detected PDE/subap/exp	53	
LO WFS Rate	226	Hz
Detected PDE/subap/exp	######	

Ice Giant Planets

Optimizations/sky coverage calculations		COO / NGAO PROPRIETARY

Purpose: This worksheet will allow one to optimize sky coverage by changing parameters
in order to balance the error budget terms; several of the Input Summary cells point to the purple cells here
How exactly to optimize depends on whether the science case is NGS, LGS on-axis, or LGS field stars (sky coverage)

Solver Input Values	NGS	LGS		Current Settings	
HO guide star brightness	8.00		mV	133	PDE/subap/exp
Optim HO integration time:	0.00050	0.0010	sec	2000	Hz
Optim subaperture width:	0.174	0.174	meters	60	Subaps
TT guide star brightness	8.0	18.0	mV	6.48	mKs
TT integration time	0.00050	0.0044	sec	2000	Hz
TT guide star distance	0.0	30.0	arcsec		
TWFS guide star birghtness	8.0	18.0	mV		
TWFS integration time	0.0	2.0000	sec	2000.00	Hz
TWFS guide star search radius	0.0	30.0	arcsec		
Number of laser beacons		4.0			
LGS asterism radius	0.0	0.167	arcmin	Set ast rad = 0.001 for single LGS	

Optimize LGS Off-Pointing?	N			
Optimize LGS Range Gate?	N			
Optimize Subap Diameter?	N	0.182	m	Non-optim subap width
Optimize LGS asterism radius?	N	<-- not yet implemented (11/18/08)		

Keck Wavefront Error Budget Summary

Version 2.1

Mode: **NGAO NGS**
Instrument: **DAVINCI**
Sci. Observation **Ice Giant Planets**

Science Band	u'	g'	r'	i'	Z	Y	J	H	K
λ (μμ)	0.36	0.47	0.62	0.75	0.88	1.03	1.25	1.64	2.20
δλ (μμ)	0.06	0.14	0.14	0.15	0.12	0.12	0.16	0.29	0.34
λ/Δ (μασ)	6.7	8.8	11.6	14.1	16.6	19.4	23.5	30.8	41.4

Science High-order Errors (NGS Mode)			Wavefront Error (rms)	Parameter	
Atmospheric Fitting Error			50 nm	60	Subaps
Bandwidth Error			40 nm	**100**	Hz (-3db)
High-order Measurement Error			151 nm	8	mV
LGS Tomography Error			0 nm	1	natural guide star
Asterism Deformation Error			0 nm	0.50	m LLT
Chromatic Error			1 nm		Upper limit
Dispersion Displacement Error			19 nm		Estimate
Multispectral Error			25 nm	30	zen; sci wav
Scintillation Error	*H*		12 nm	0.34	Scint index at 0.5um
WFS Scintillation Error			10 nm		Allocation
		168 nm			
Uncorrectable Static Telescope Aberrations			43 nm	64	Acts Across Pupil
Uncorrectable Dynamic Telescope Aberrations			17 nm		Dekens Ph.D
Static WFS Zero-point Calibration Error			25 nm		Allocation
Dynamic WFS Zero-point Calibration Error			20 nm		Allocation
Leaky Integrator Zero-point Calibration Error			10 nm		Allocation
Stale Reconstructor Error			15 nm		Allocation
Go-to Control Errors			0 nm		Allocation
Residual Na Layer Focus Change			0 nm	30	m/s Na layer vel
DM Finite Stroke Errors			8 nm	5.3	um P-P stroke
DM Hysteresis			13 nm		from TMT model
High-Order Aliasing Error			11 nm	60	Subaps
DM Drive Digitization			1 nm	16	bits
Uncorrectable AO System Aberrations			25 nm		Allocation
Uncorrectable Instrument Aberrations			30 nm		DAVINCI
DM-to-lenslet Misregistration			15 nm		Allocation
DM-to-lenslet Pupil Scale Error			15 nm		Allocation
		76 nm			
Angular Anisoplanatism Error			16 nm	1.0	arcsec
HO Wavefront Error Margin			45 nm		Allocation
Total High Order Wavefront Error		184 nm	**190 nm**	**High Order Strehl**	

Strehl Ratio (%)	u'	g'	r'	i'	Z	Y	J	H	K
High Order Strehl	0.00	0.00	0.03	0.08	0.17	0.27	0.41	0.59	0.75

Science Tip/Tilt Errors	Sci Filter	Angular Error (rms)	Equivalent WFE (rms)	Parameter	
Tilt Measurement Error (one-axis)		3.92 mas	66 nm	**8.0**	mag (mV)
Tilt Bandwidth Error (one-axis)		0.25 mas	4 nm	**50.0**	Hz (-3db)
Tilt Anisoplanatism Error (one-axis)		0.00 mas	0 nm	**0.0**	arcsec from sci
Residual Centroid Anisoplanatism		0.00 mas	0 nm	NGS	x reduction
Residual Atmospheric Dispersion	*H*	0.26 mas	5 nm	20	x reduction
Induced Plate Scale Deformations		0.00 mas	0 nm	0	m conj height
Non-Common-Path Tip-Tilt Errors		0.00 mas	0 nm	3.2 mas/l	Allocation
Residual Telescope Pointing Jitter (one-axis)		0.23 mas	4 nm	29	Hz input disturbance
TT Error Margin		2.00 mas	145 nm		Allocation
Total Tip/Tilt Error (one-axis)		**4.4 mas**	81 nm	**Tip/Tilt Strehl**	

Strehl ratios (%)	u'	g'	r'	i'	Z	Y	J	H	K
Tip/Tilt Strehl	0.32	0.45	0.58	0.67	0.74	0.80	0.85	0.91	0.95
Total Effective Wavefront Error: **204 nm** — Total Strehl (%)	0.00	0.00	0.01	0.06	0.12	0.22	0.35	0.54	0.71
FWHM (mas)	8.0	9.8	12.4	14.7	17.2	19.9	24.0	31.1	41.7

Ensquared Energy (*H*)	Spaxel / Aperture Diameter (mas)	15	35	50	70	90	120	240	400	800		44
	Square	0.11	0.39	0.52	0.59	0.60	0.61	0.63	0.66	0.70		0.50
	Seeing-Limited	0.00	0.00	0.01	0.02	0.03	0.05	0.18	0.42	0.88		

Sky Coverage	Galactic Latitude	N/A	deg
Corresponding Sky Coverage		######	This fraction of sky can be corrected to the Total Effective WFE shown

Assumptions / Parameters

Atmospheric / Observing Parameters			System Parameters			
Zenith Angle	30	deg	LGS Asterism Radius	0.00	arcmin	
r0	0.147	m	LGS Power	NGS	W	
theta0_eff	2.145	arcsec	BTO Transmission	1.00		
Wind Speed	10.97	m/s	HO WFS Transmission	0.24		
Outer Scale	50	m	HO WFS Type	SH	using	CCID74
Sodium Abundance	3	x 109 cm-2	HO WFS Noise	2.6	e- rms	
			HO WFS Anti-aliasing	YES		
AO Modes of Operation			LO WFS Transmission	0.24		
Science AO Mode:	SCAO		LO WFS Type	NGS	using	CCID74
LOWFS AO Mode:	0.00		LO WFS Noise	2.6	e- rms	
			LO WFS Star Type:	G		
Number of WFS's for TT measurement			Max TT Rejection Bandwidth	100	Hz	
TT	0					
TTFA	0		**Observation Parameters**			
3x3	0		Max Exposure Time	2	sec	
HOWFS	1					

LO WFS Magnitudes								
9.1	7.7	7.3	7.2	7.1	7.0	6.8	6.5	6.5

Derived Values		
HO WFS Rate	2000	Hz
Detected PDE/subap/exp	133	
LO WFS Rate	2000	Hz
Detected PDE/subap/exp	311487	

Appendix B: Atmospheric Turbulence Assumptions

The following are detailed wavefront error / ensquared energy budgets developed using the median turbulence condition Mauna Kea Ridge $C_n^2(h)$ model (KAON 503). This model has:

r_0 (0.5 microns) = 16 cm

θ_0 (0.5 microns) = 2.7 arcseconds

d_0 (0.5 microns) = 4.85 m

L_0 = 50 m

with a $C_n^2(h)$ distribution given by:

Altitude (m)	Mauna Kea Ridge Cn2 Fractional Turbulence
0	0.517
500	0.119
1000	0.063
2000	0.061
4000	0.105
8000	0.081
16000	0.054

KAON 503 also defines a wind velocity model for the Mauna Kea Ridge resulting in:

Greenwood frequency = 27.91 Hz